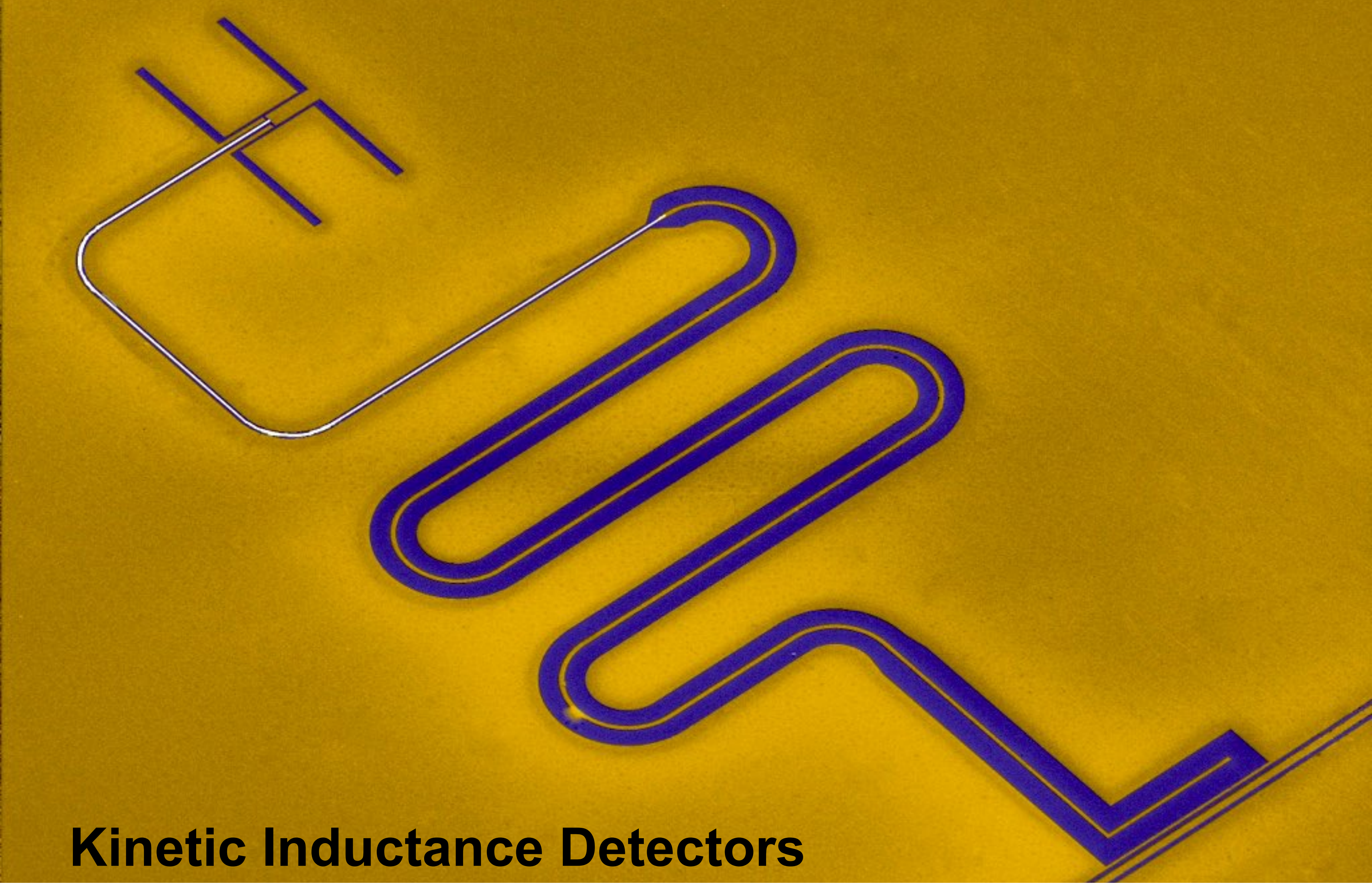


Kinetic Inductance Detectors

Reinier Janssen

March 28, 2019

Jet Propulsion Laboratory
California Institute of Technology

Outline

- Introduction
- Kinetic Inductance Detector
  - operational principle
  - limiting noise sources
- Hybrid NbTiN-Al Kinetic Inductance Detector
  - design philosophy
  - performance
- Instruments
  - mm/sub-mm imaging cameras
  - mm/sub-mm on-chip spectrometers
  - UVOIR imaging spectrometers
- Summary

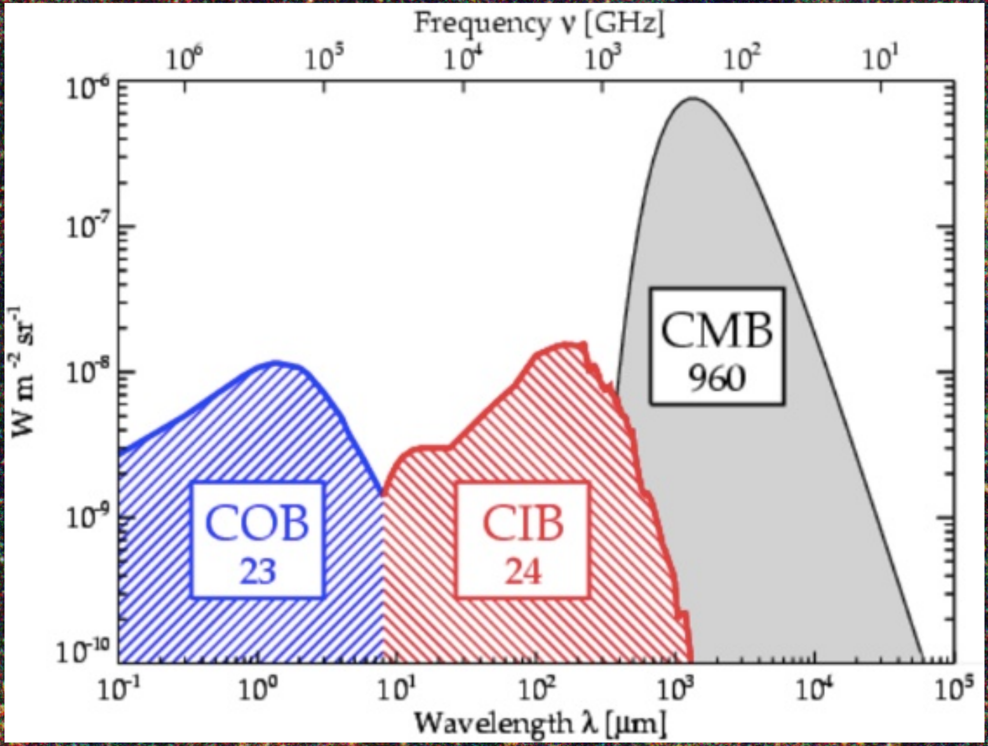
TU Delft

SRON
Netherlands Institute for Space Research

JPL
Jet Propulsion Laboratory
California Institute of Technology

PhD Thesis: http://repository.tudelft.nl
Baselmans et al., A&A **601** A89 (2017)

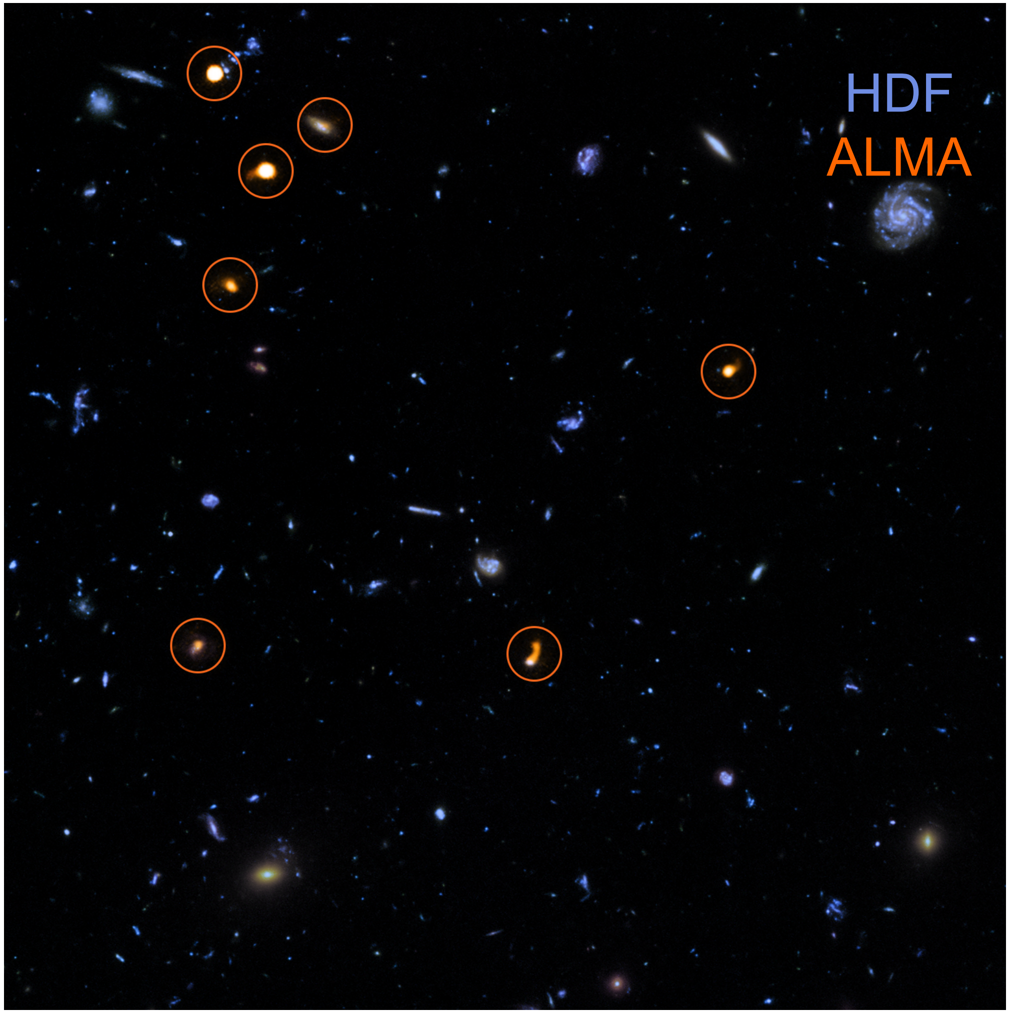
Extragalactic background radiation



30 arcmin

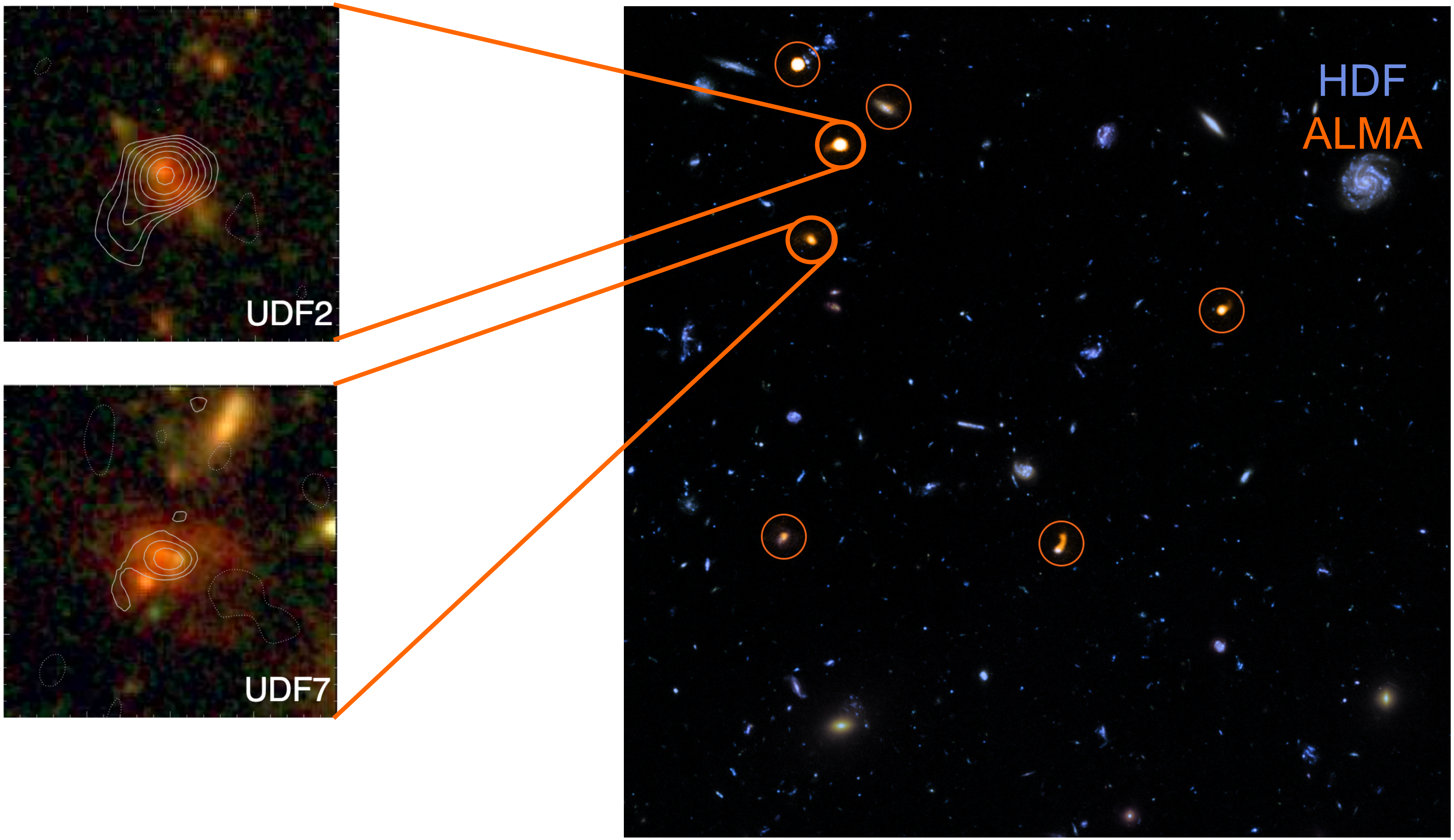
Lockman Hole
Herschel-SPIRE
250, 350, 500 µm composite

Different galaxy populations



Dunlop et al, MNRAS 2017

Different galaxy populations



Dunlop et al, MNRAS 2017

ALMA

State of the Art in Sub-mm Astronomy

ALMA is revolutionizing the field of sub-mm astronomy

Limitations of ALMA:
- Limited Field of View
- Limited Instantaneous Bandwidth
- Oversubscription factor 5 -10

Complement ALMA with a single dish instruments
- Large Field of View Camera
- Broadband spectrometers

Future instrumentation for sub-mm astronomy

ALMA is revolutionizing the field of sub-mm astronomy

Limitations of ALMA:

- Limited Field of View
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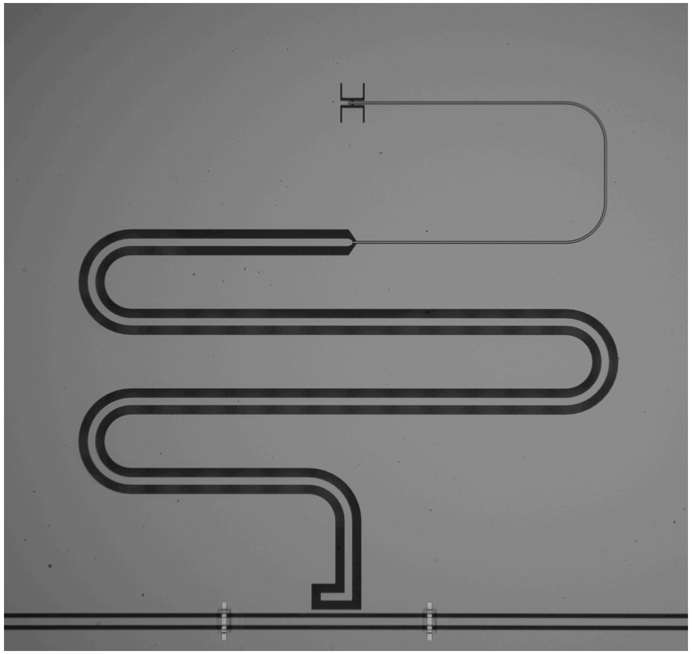
Complement ALMA with a single dish instruments

- Large Field of View Camera
- Broadband spectrometers

Kinetic Inductance Detector

Superconducting resonator optimized for radiation detection

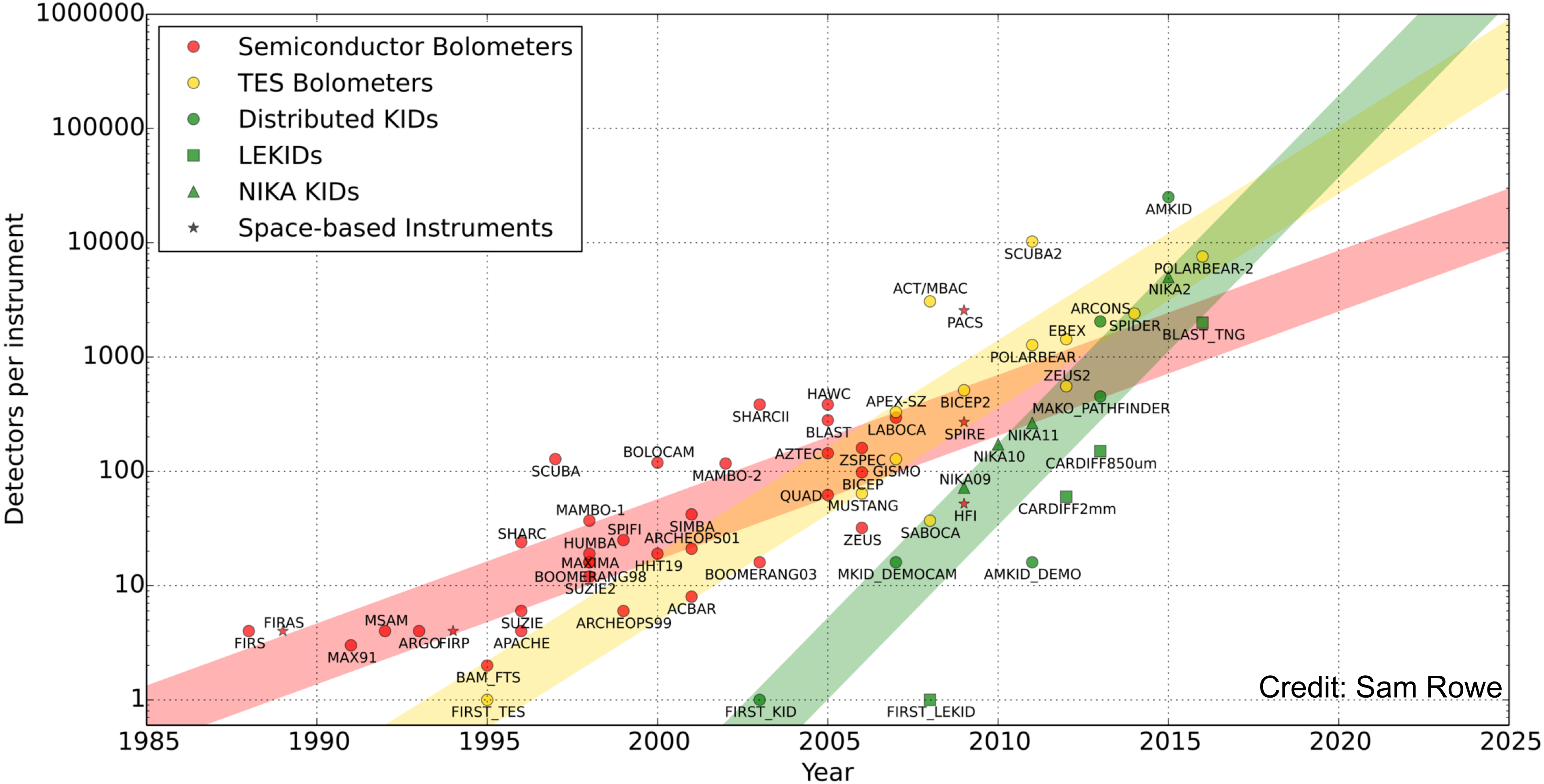


Distributed resonator

Lumped element resonator

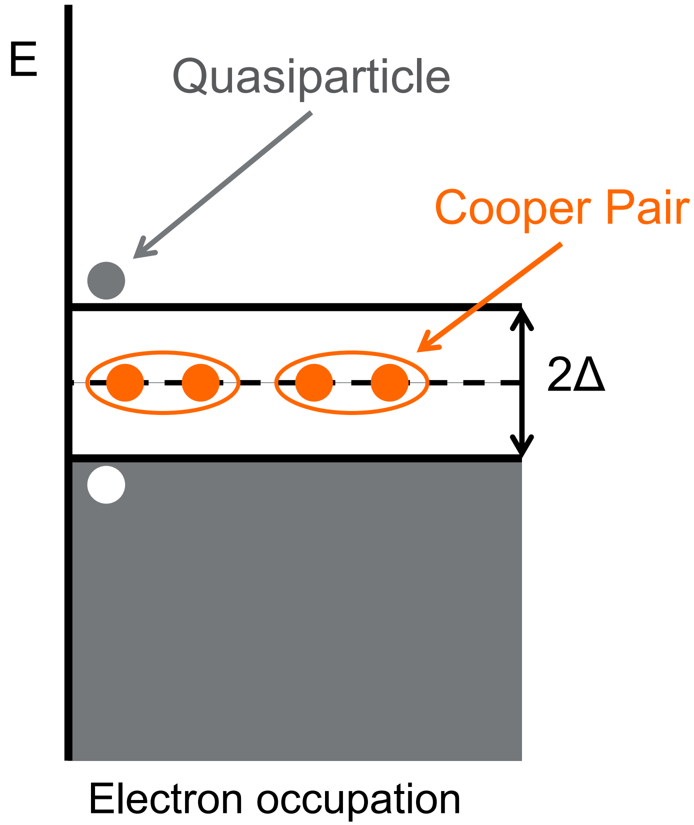
Kinetic Inductance Detector

Frequency Domain Multiplexing



Pair breaking detector

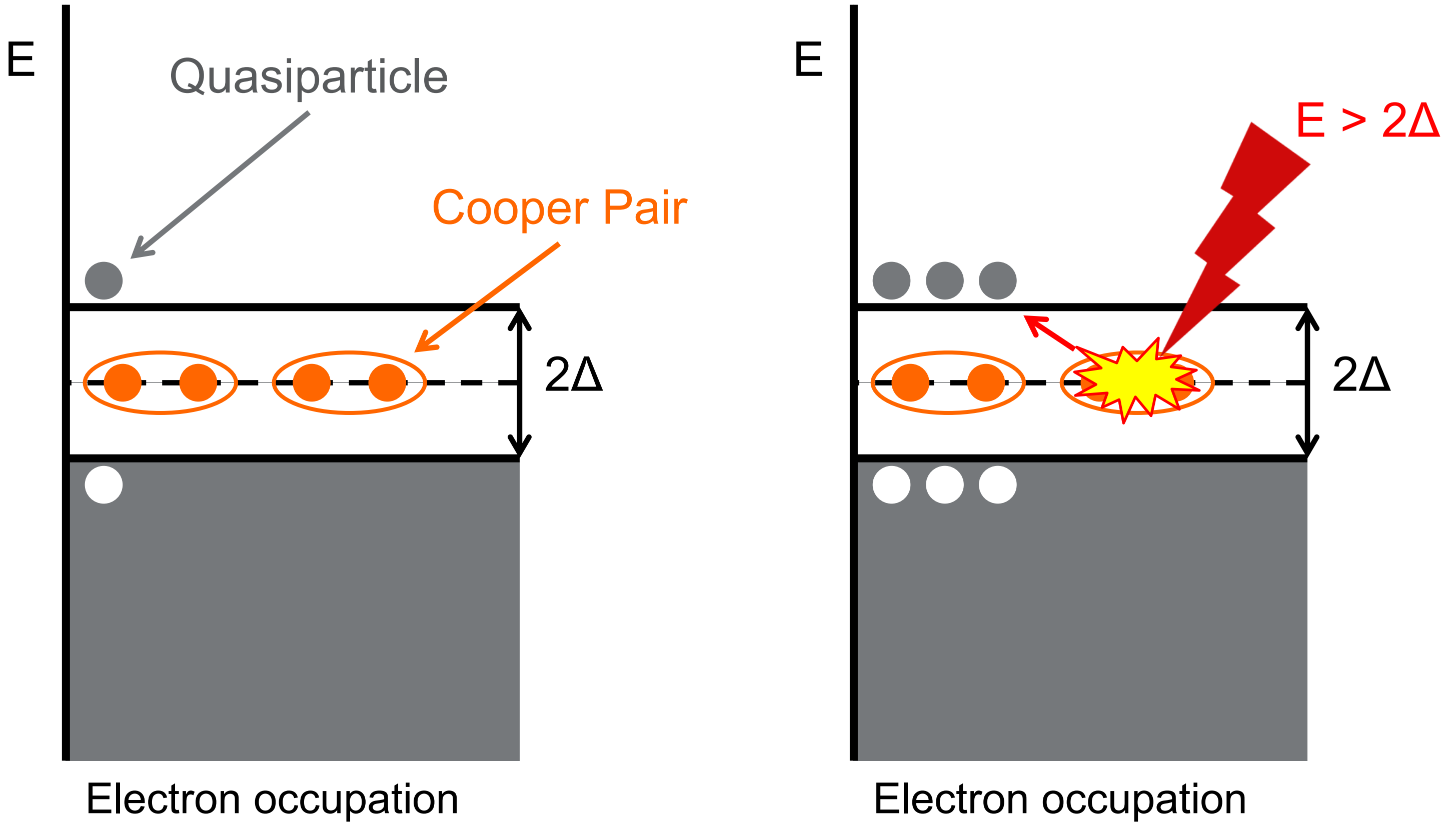
$\sigma = \sigma_1 - i\sigma_2$



Pair breaking detector

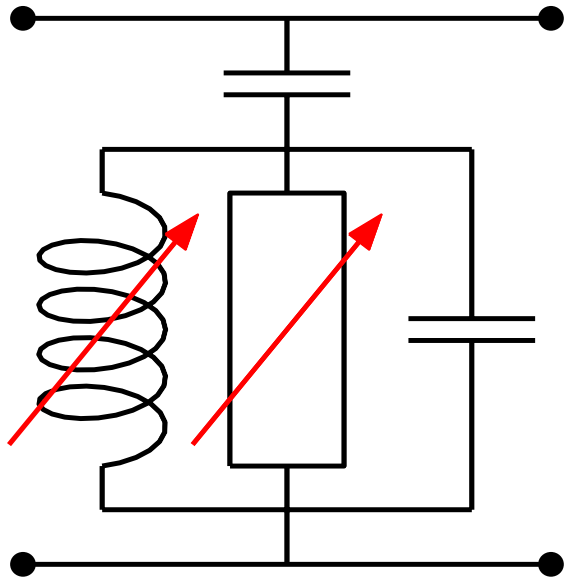
$\sigma = \sigma_1 - i\sigma_2$

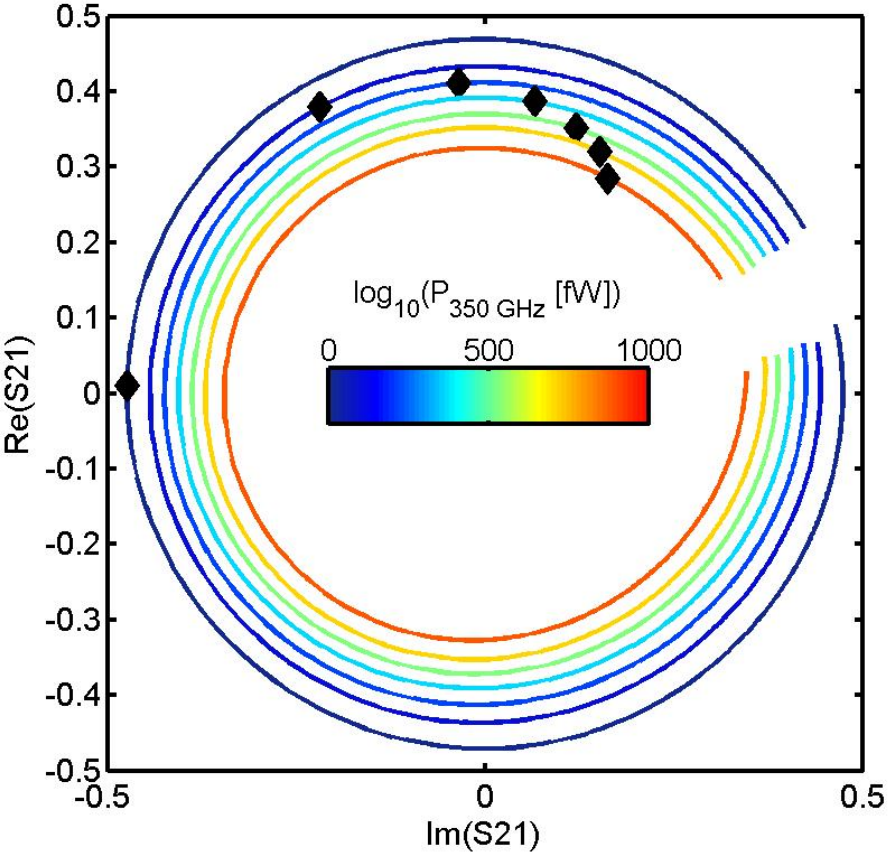
$\sigma = \sigma_1(N_{qp}) - i\sigma_2(N_{qp})$



KID operation principle

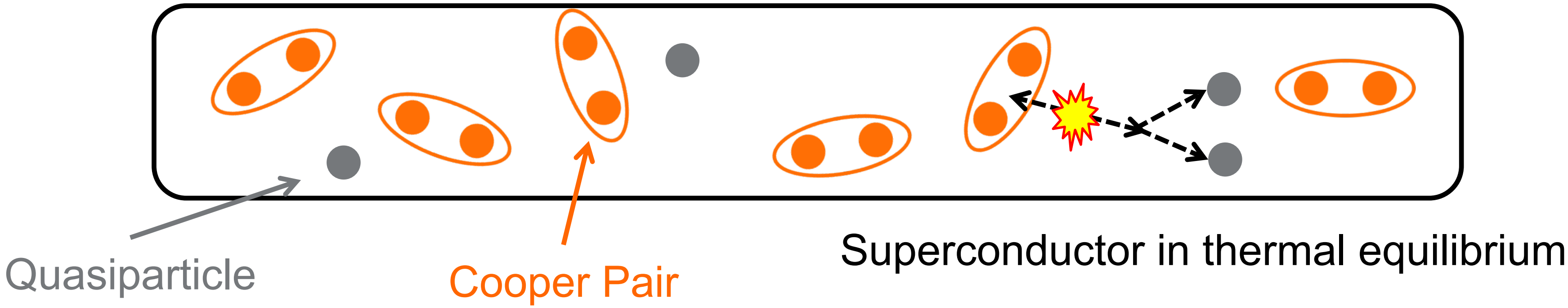
Superconducting resonator
$Q \sim 10^4 - 10^6$
$F_{res} \sim 1$ -10 GHz





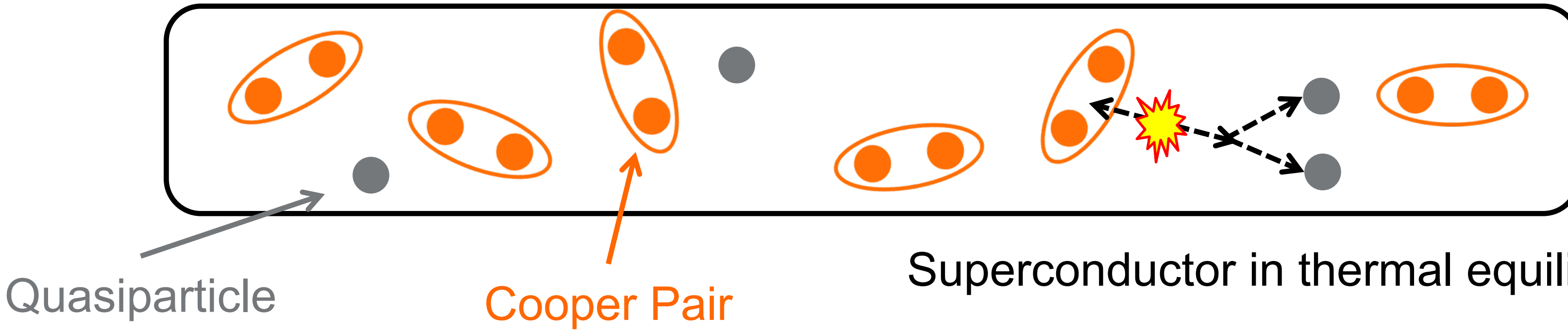
Generation – Recombination (GR) Noise

Fundamental sensitivity limit



Generation – Recombination (GR) Noise

Fundamental sensitivity limit

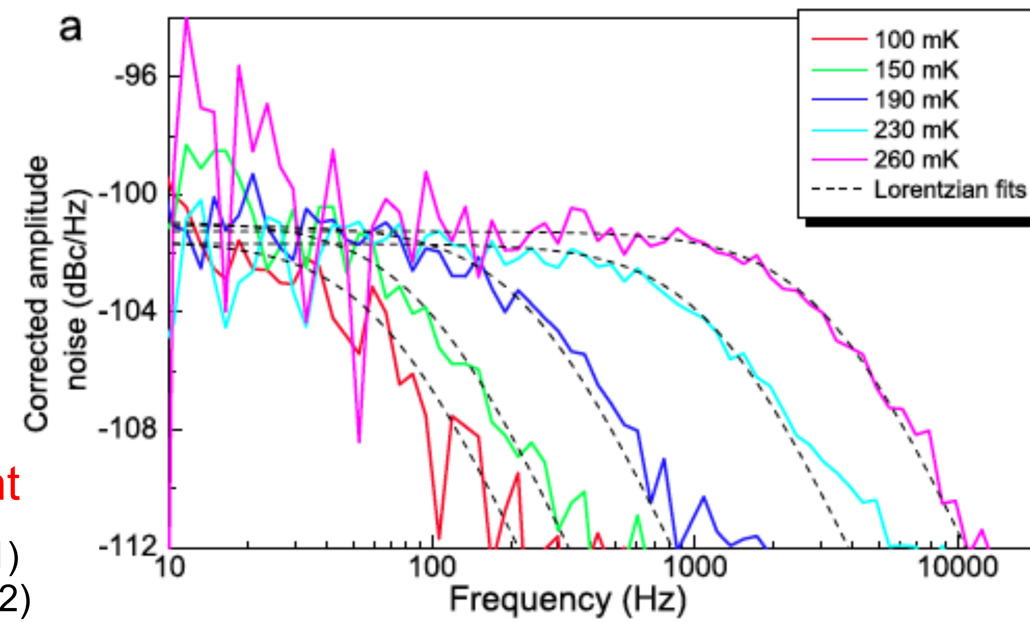


Superconductor in thermal equilibrium

Temperature independent

$$S_N = \frac{4\boxed{N_{qp}\tau}}{1+\omega^2\tau^2}$$

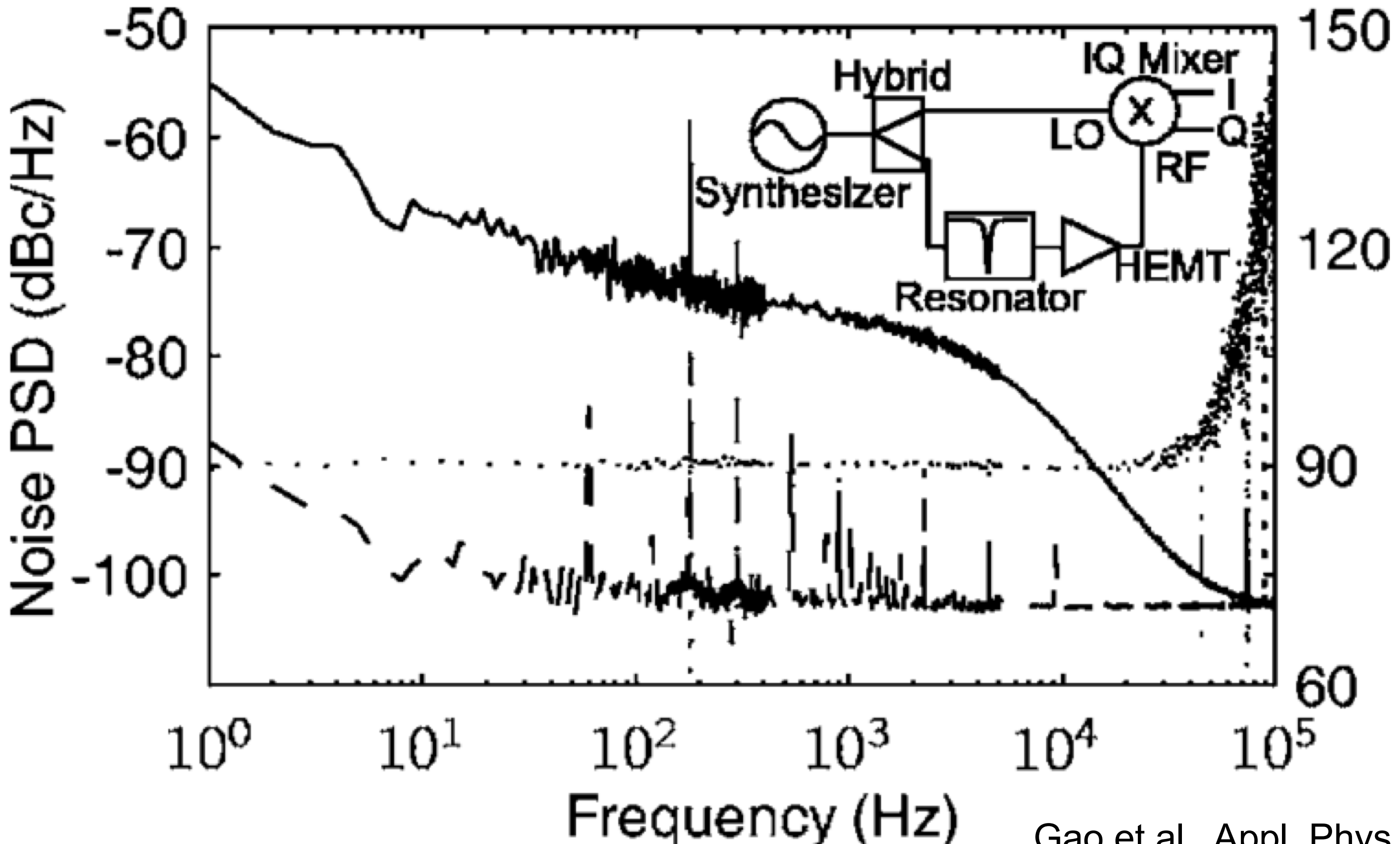
Temperature dependent



De Visser et al., Phys. Rev. Lett. **106** 167004 (2011)
De Visser et al., Appl. Phys. Lett. **100** 162601 (2012)

Two-level-system (TLS) noise

Excess phase noise

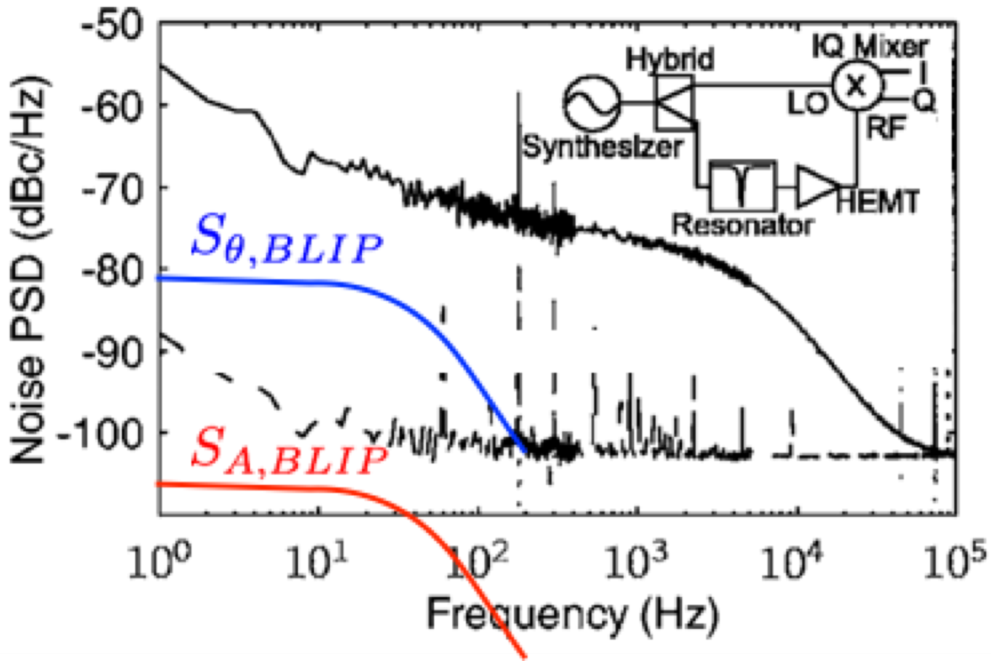


Gao et al., Appl. Phys. Lett. **90** 102507 (2007)

Photon-noise-limited performance

Goal sensitivity

$$S_{BLIP} = 2Ph\nu(1+mB)\frac{(dx/dP)^2}{1+(2\pi\tau_{qp}\nu)^2} \propto \frac{N_{qp}\tau_{qp}}{1+(2\pi\tau_{qp}\nu)^2}\left(\frac{dx}{dN_{qp}}\right)^2$$



To achieve photon-noise-limited performance:

- Reduce S_{MKID}
- Increase response
- (Use amplitude readout)

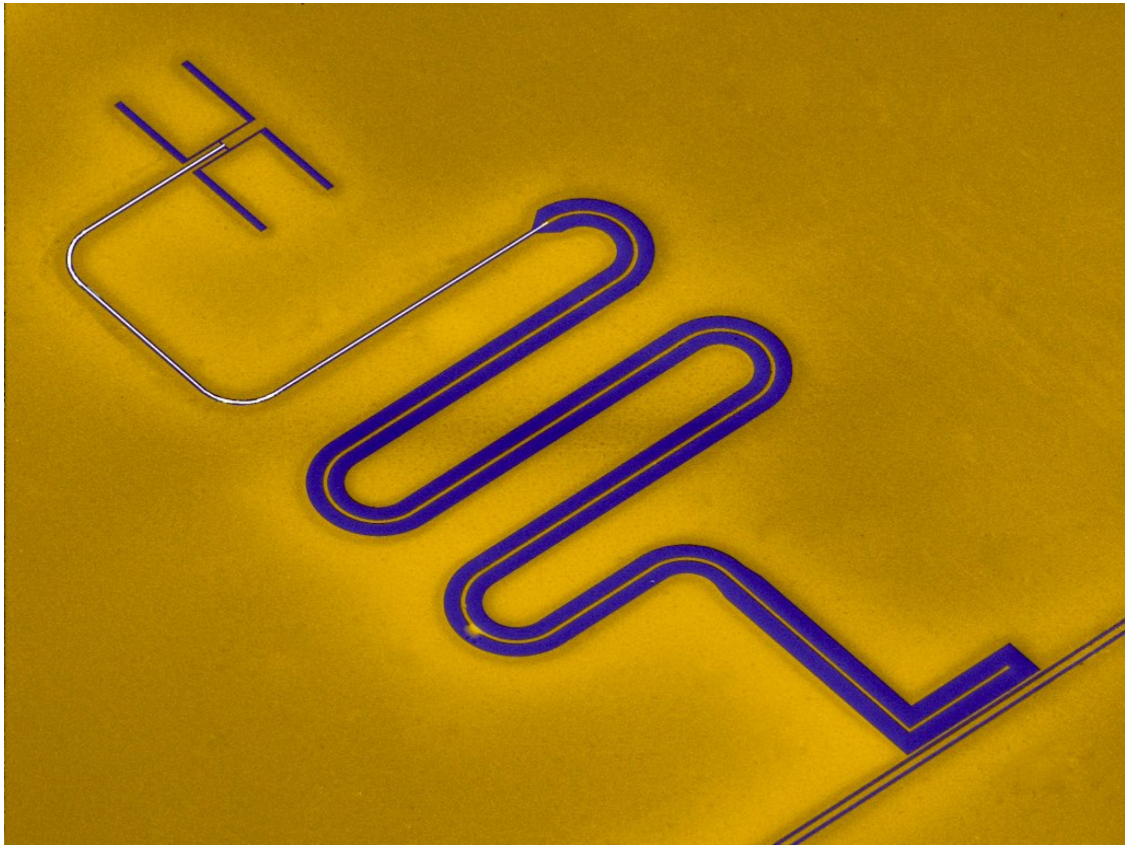
Hybrid NbTiN-Al MKID design

Design Goals:

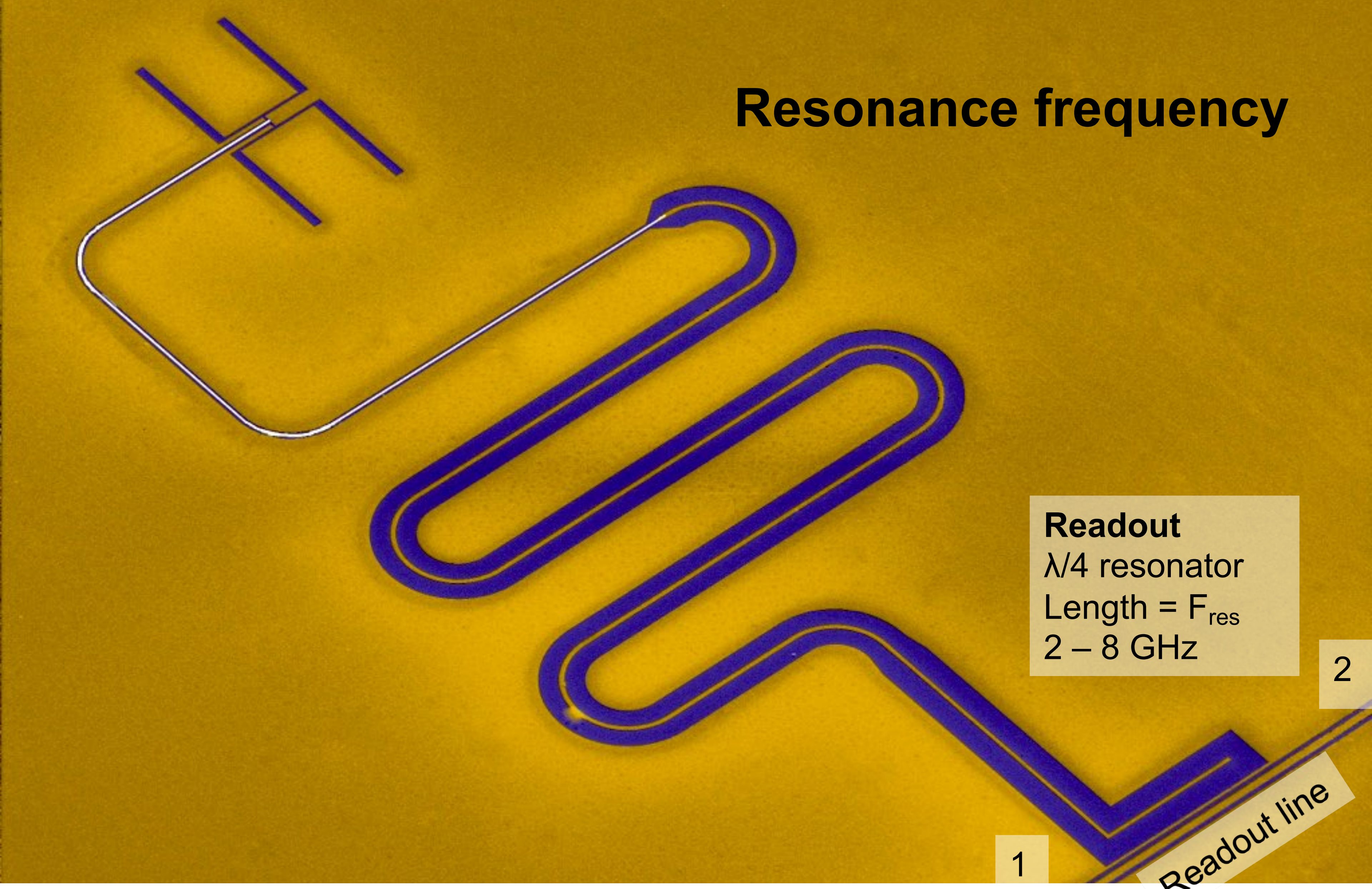
- Low (phase) noise
- High response
- High optical efficiency
- High multiplexing factor

Combining the best of

- NbTiN
- Al

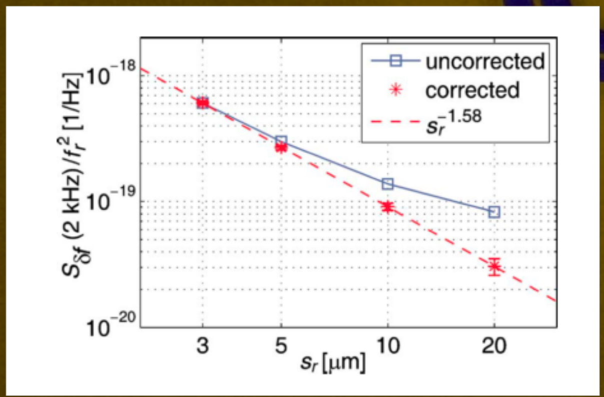


Resonance frequency

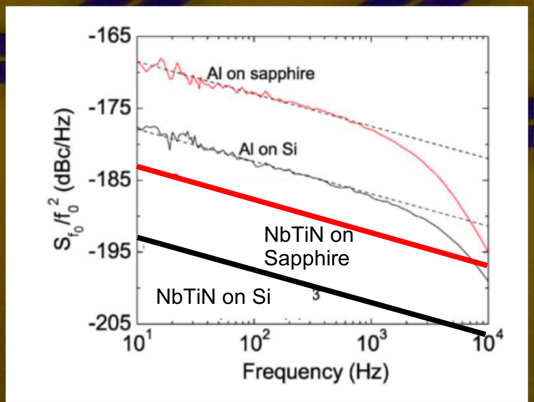


Wide NbTiN CPW

Lossless F < 1.1 THz



Gao et al., APL (2008)



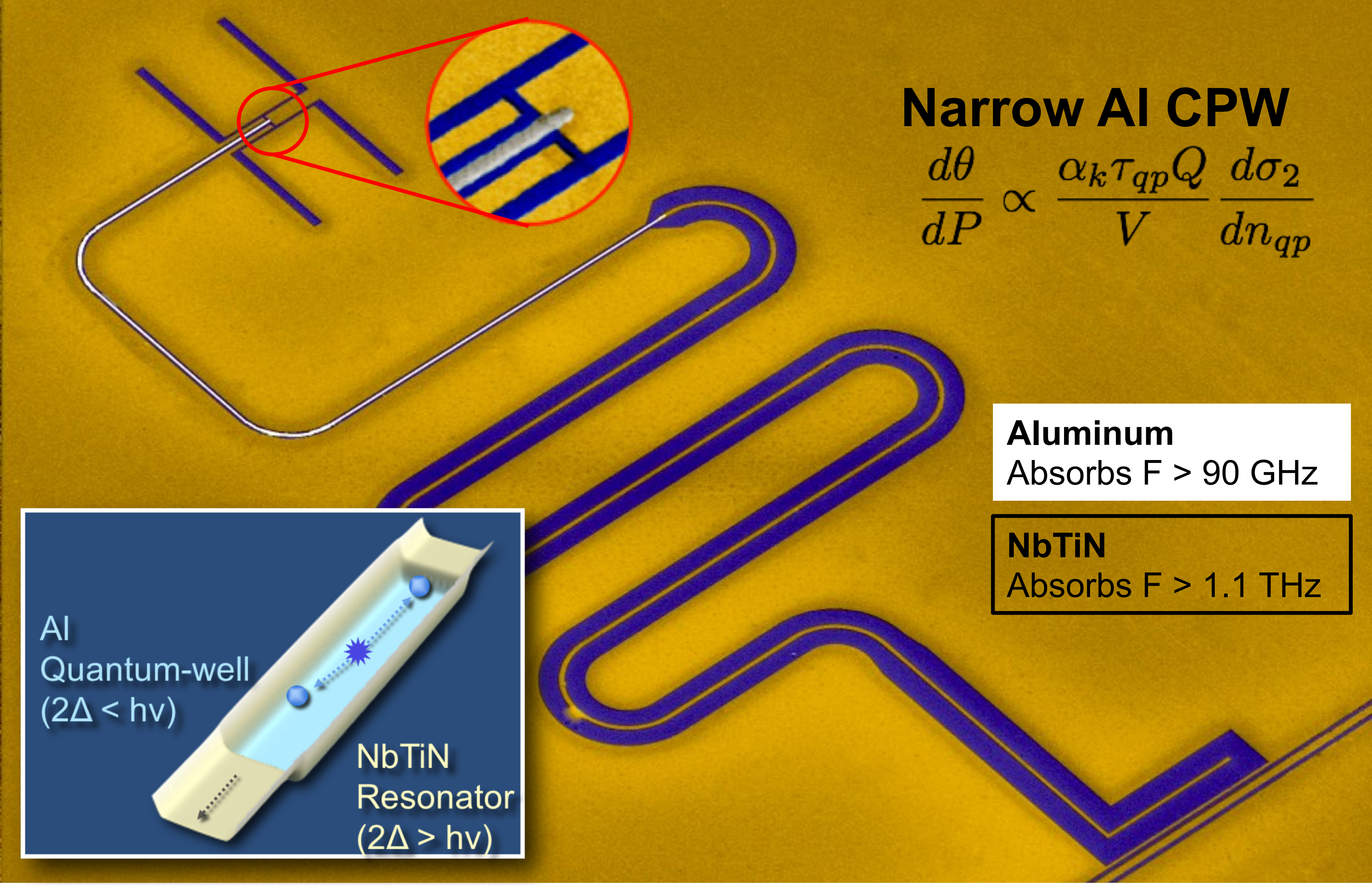
Barends et al., IEEE TAS (2009)

Narrow Al CPW

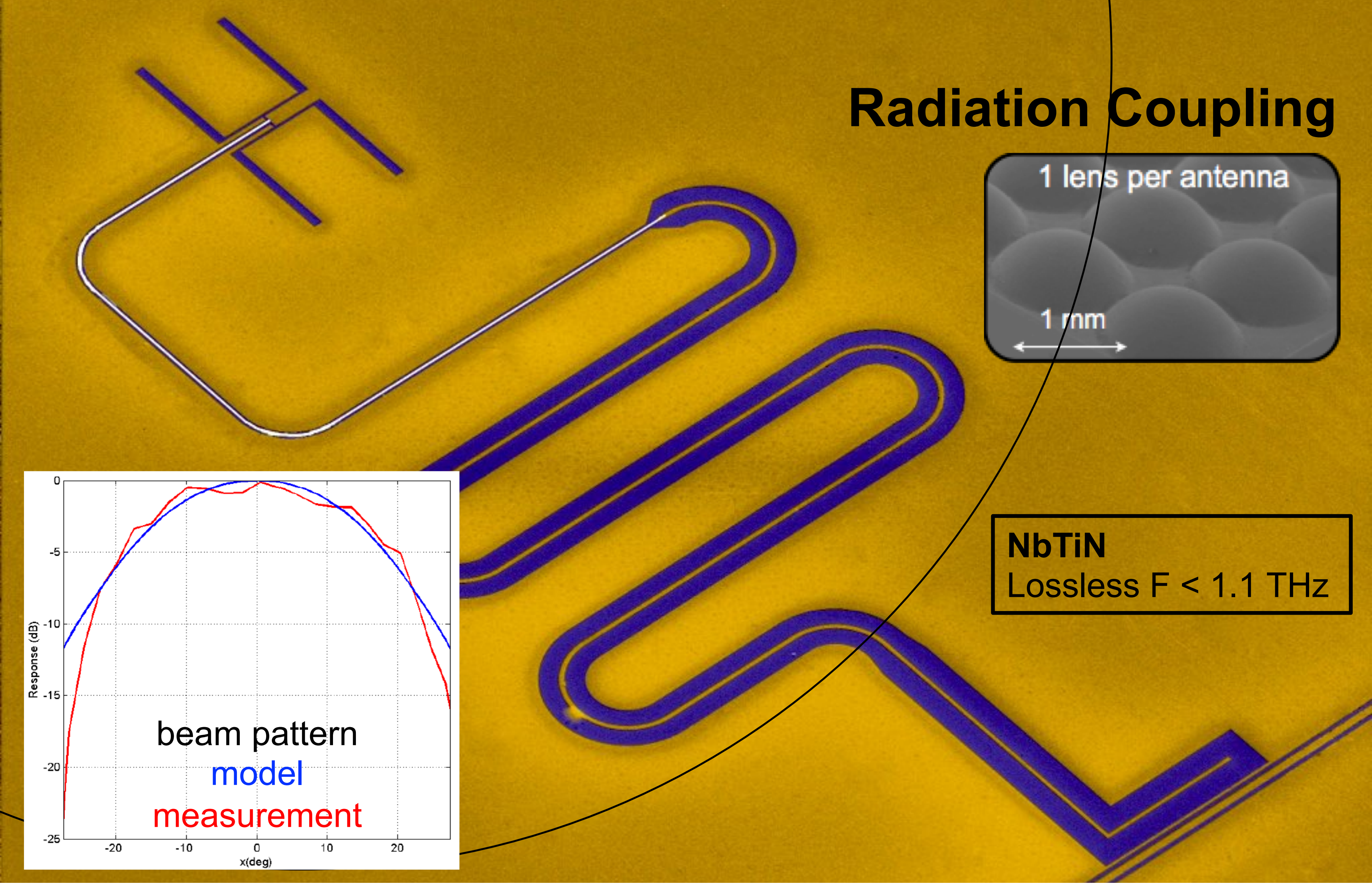
$$\frac{d\theta}{dP} \propto \frac{\alpha_k \tau_{qp} Q}{V} \frac{d\sigma_2}{dn_{qp}}$$

Aluminum
Absorbs F > 90 GHz

NbTiN
Absorbs F > 1.1 THz

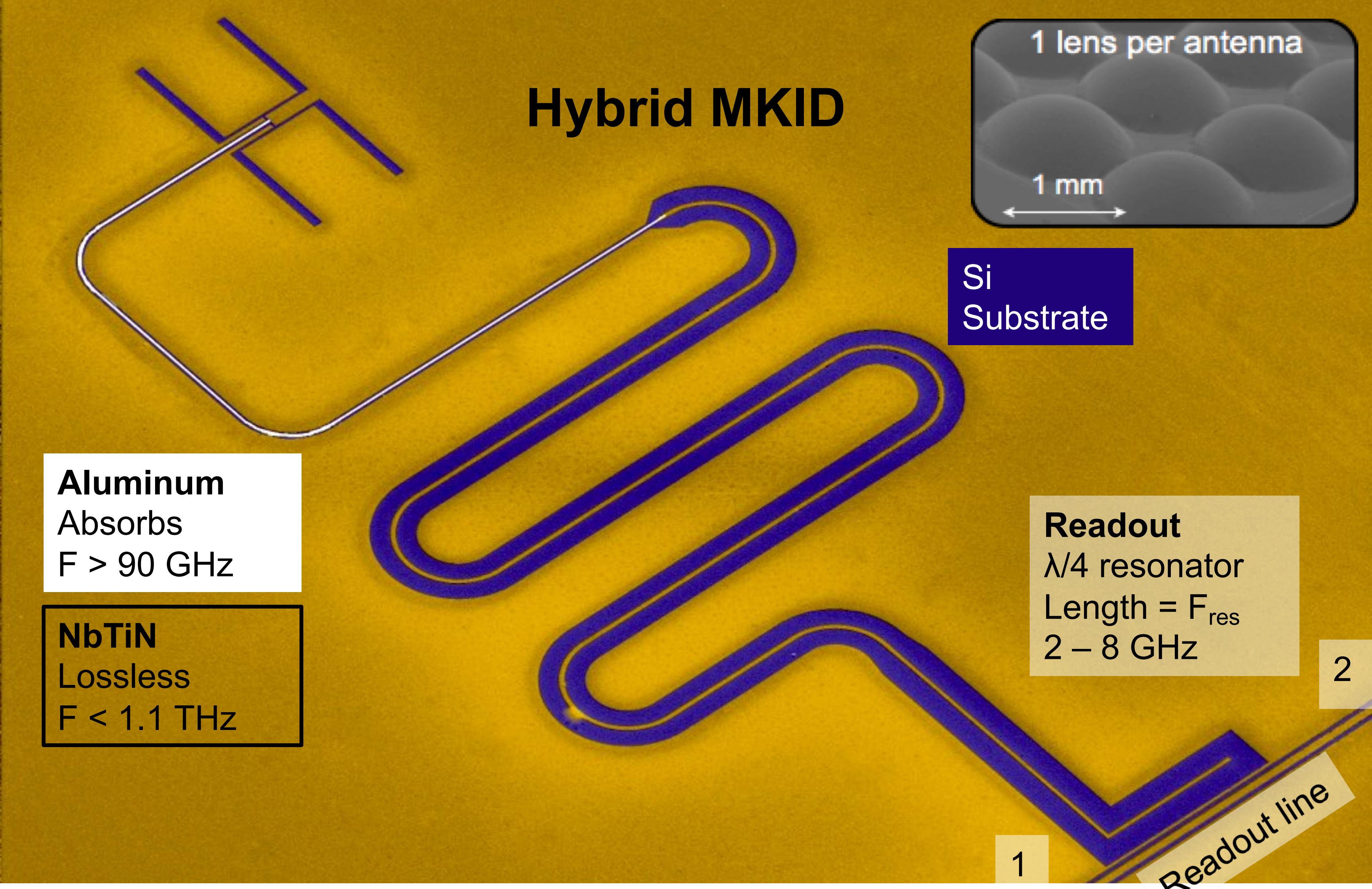


Radiation Coupling

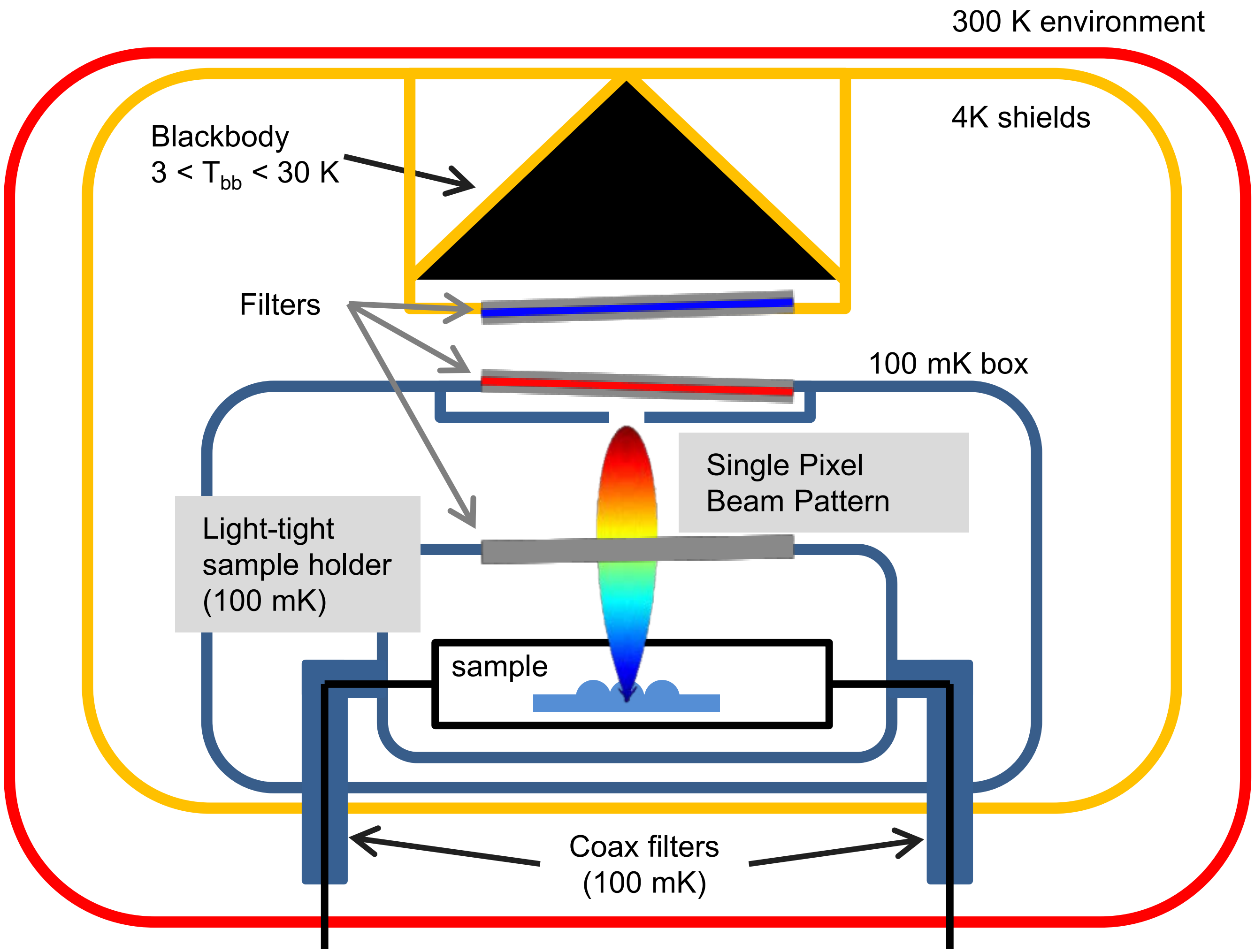


NbTiN
Lossless F < 1.1 THz

Hybrid MKID


1 lens per antenna
1 mm
Si
Substrate
Aluminum
Absorbs
F > 90 GHz
NbTiN
Lossless
F < 1.1 THz
Readout
λ/4 resonator
Length = F_{res}
2 – 8 GHz
2
1
Readout line

Experimental Setup



Absorbed optical power

Absorbed power

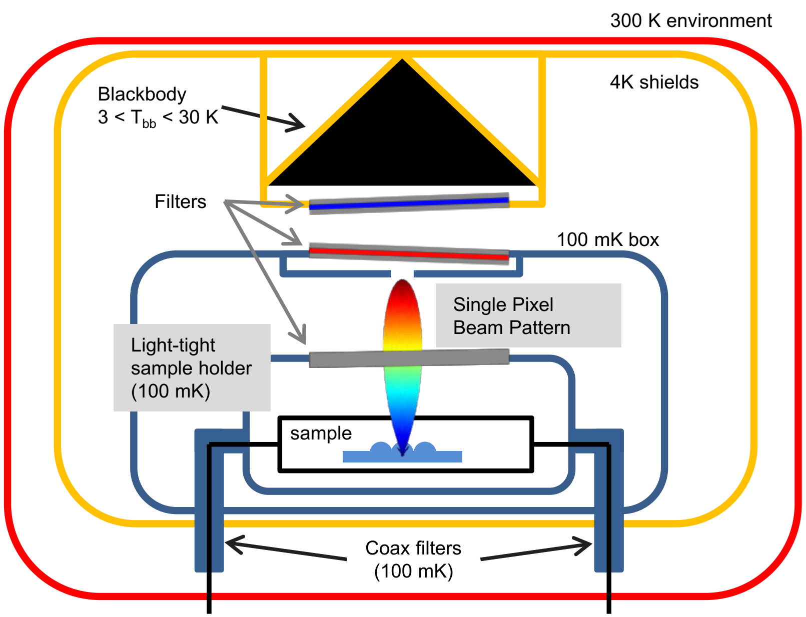
Illumination source

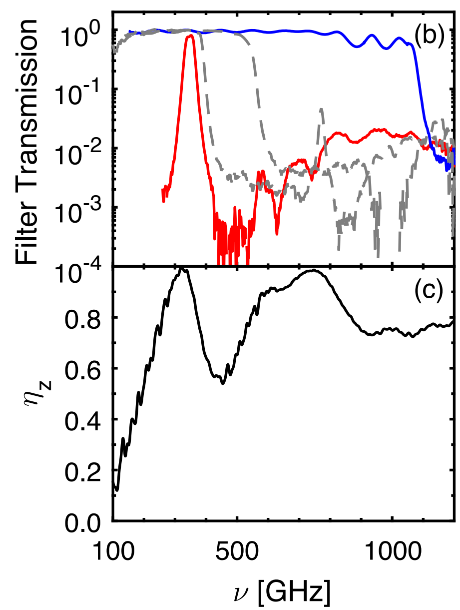
$$P_{abs} = \frac{1}{4\pi}\int_{\nu}\int_{\Omega\in A_{ap}} \frac{c^2}{2\nu^2} F_\nu B_\nu(T_{BB})\; C_\nu G_\nu(\Omega)\; d\Omega d\nu$$

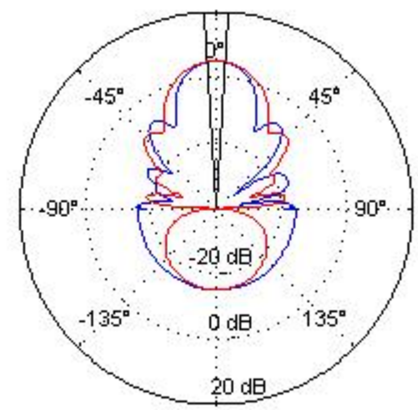
Geometry setup

Filters

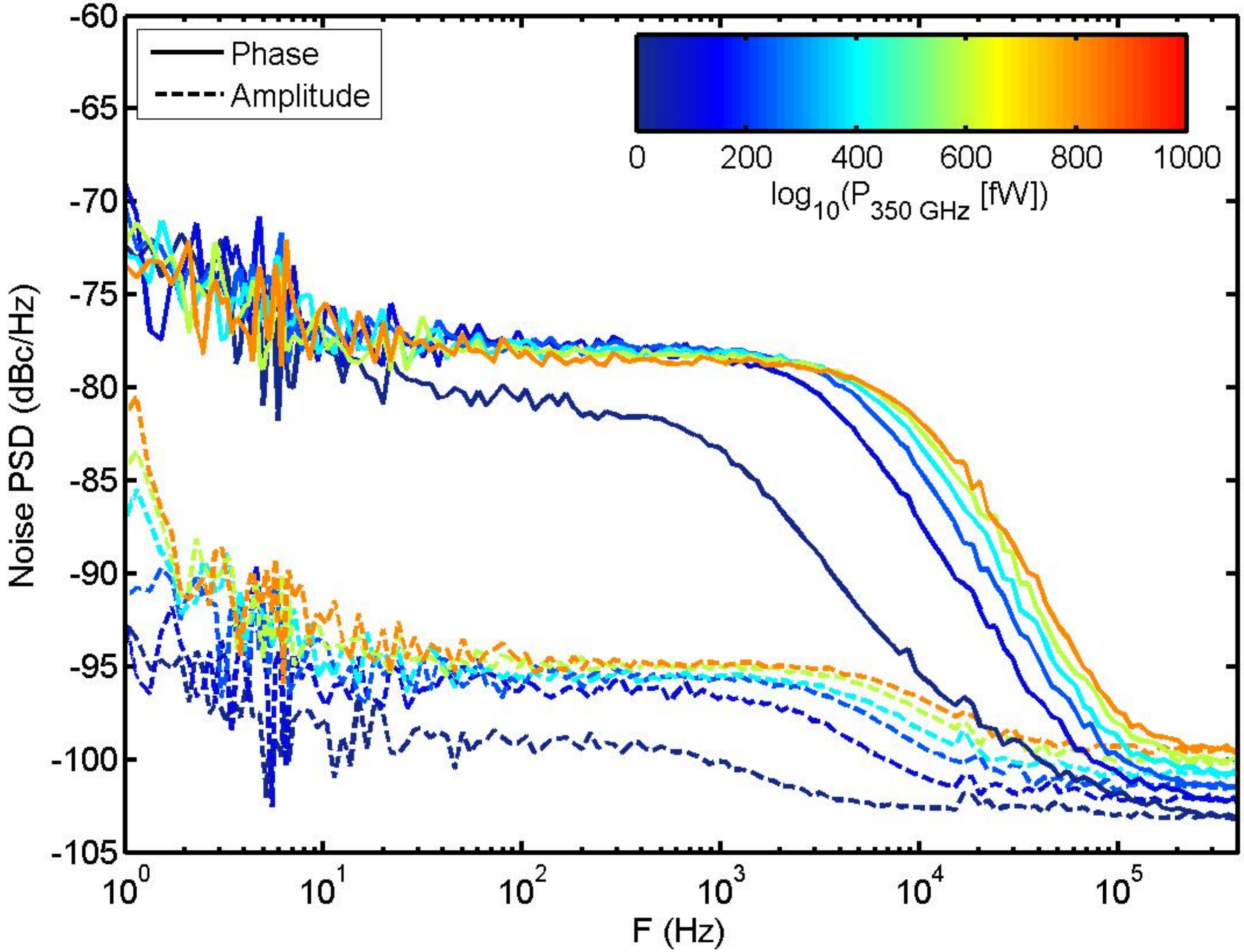
Beam pattern



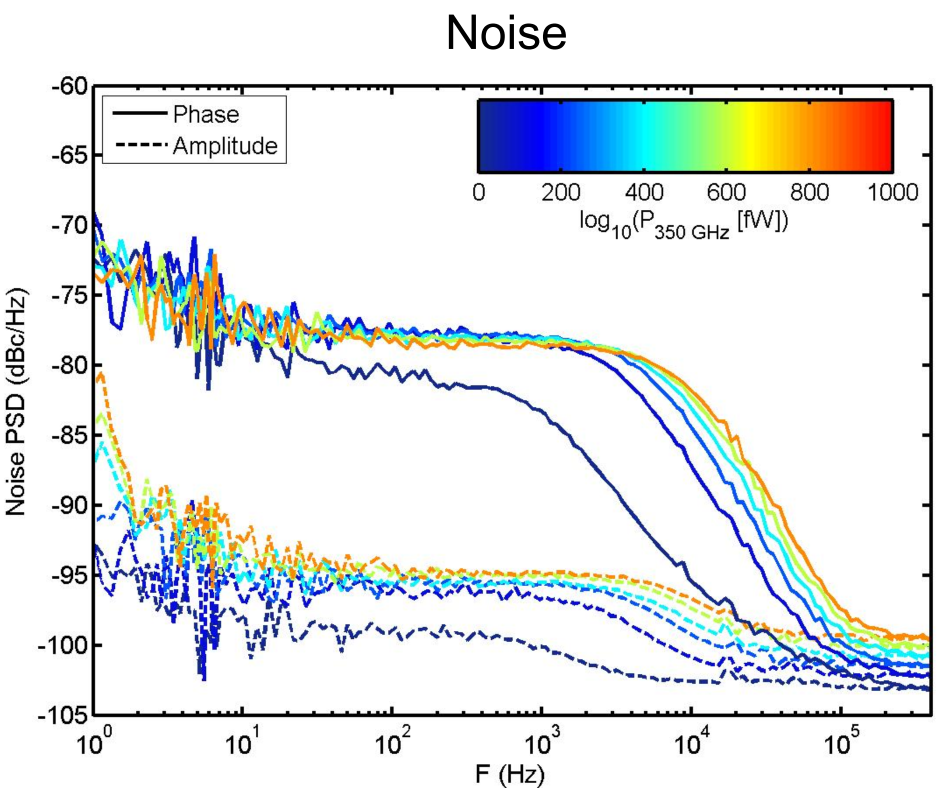


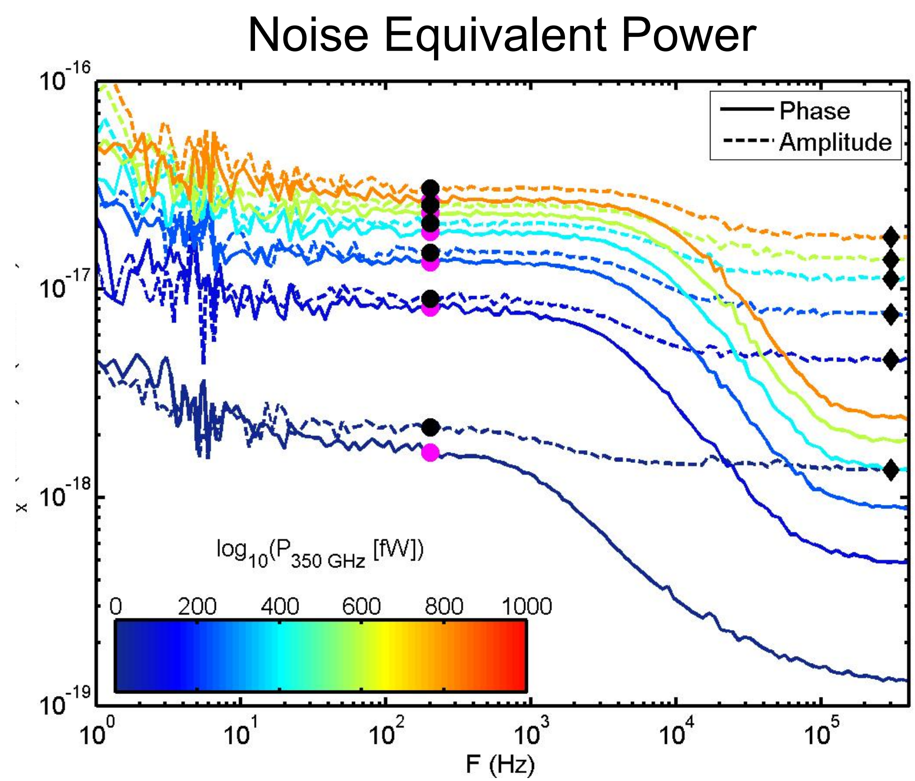


Photon-noise limited performance

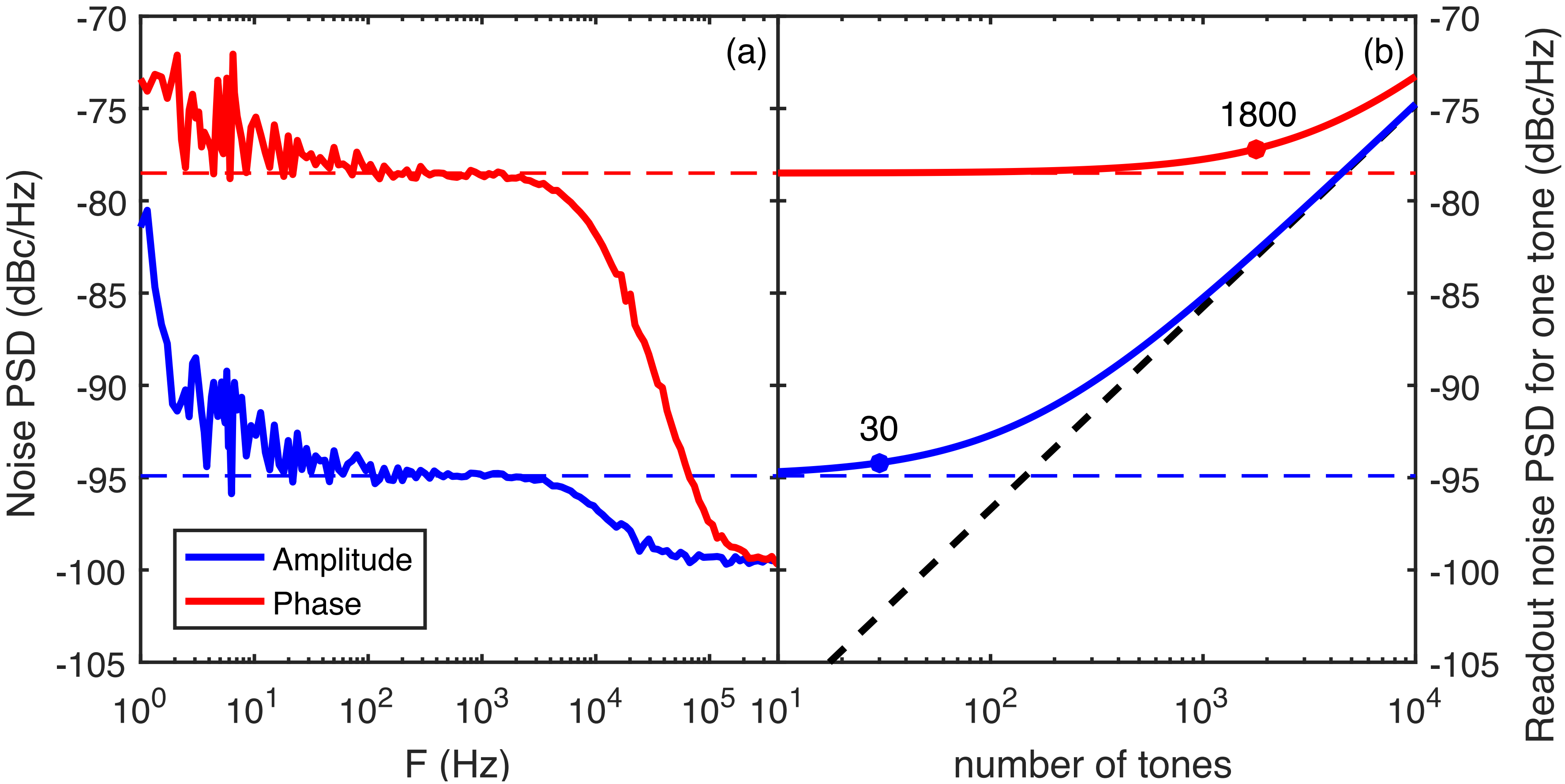


Photon-noise limited performance in *phase* readout





Multiplexing: *phase* readout preferred

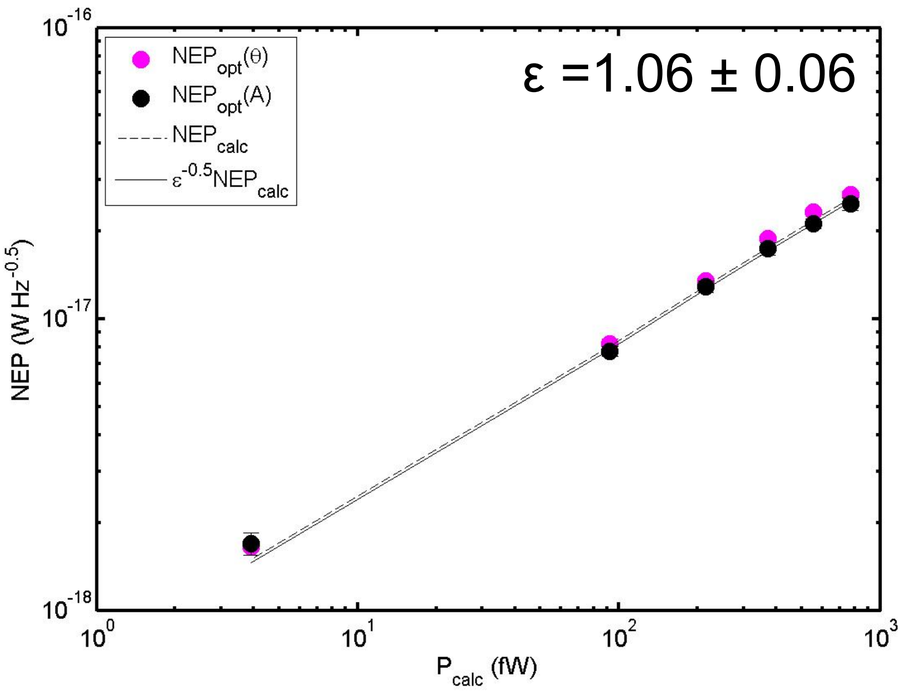


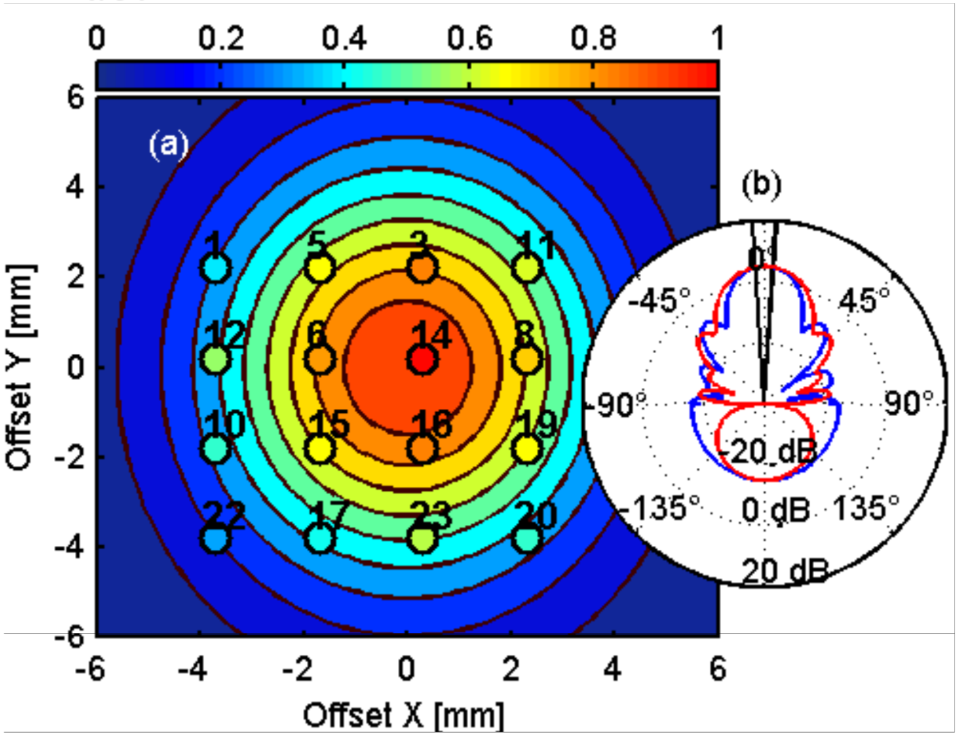
Absorbed optical power

Calculation vs measurement

$$P_{abs} = \epsilon P_{calc}$$

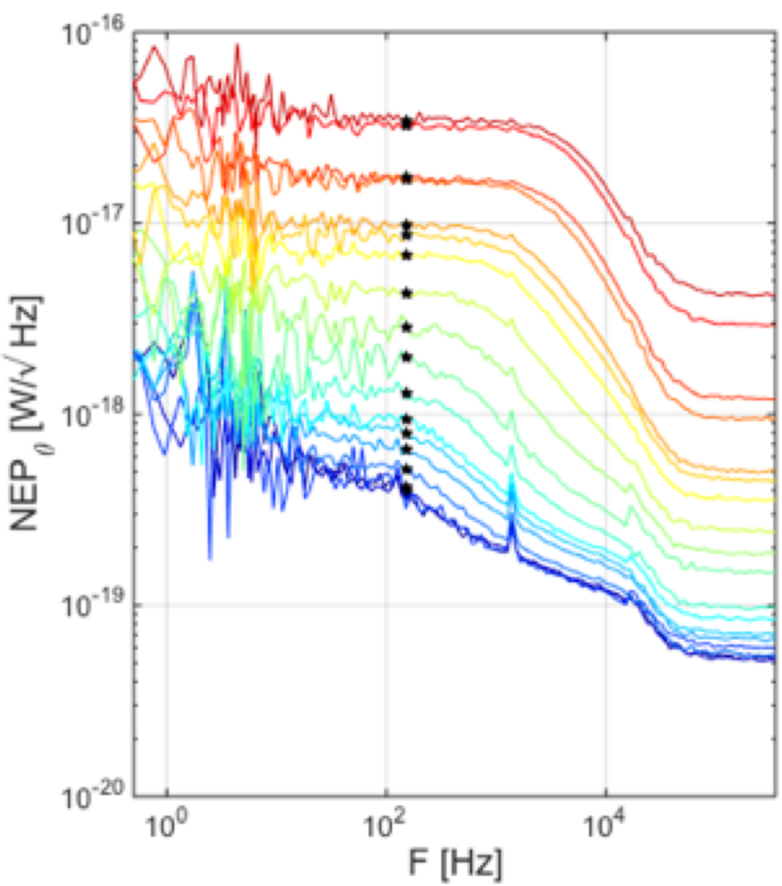
$$\epsilon = \frac{NEP^2_{calc}}{NEP^2_{meas}} = \frac{2P_{calc}(h\nu + \Delta/\eta_{pb})}{NEP^2_{200Hz} - NEP^2_{det}}$$

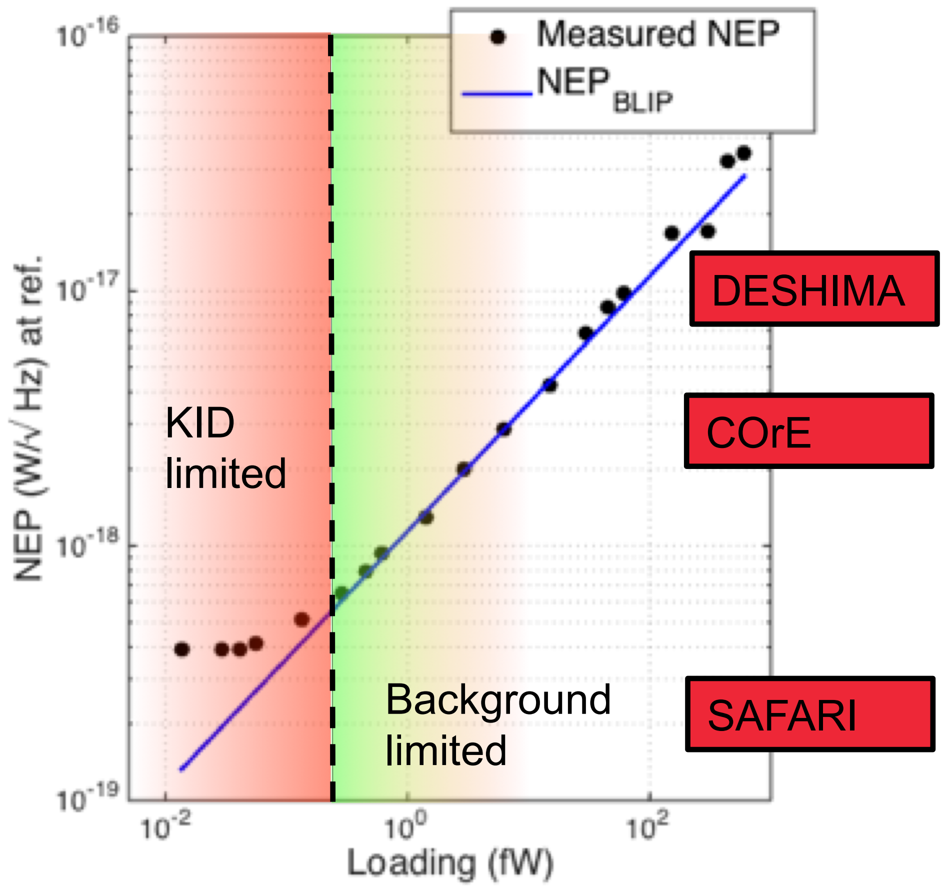




Hybrid NbTiN-Al KIDs

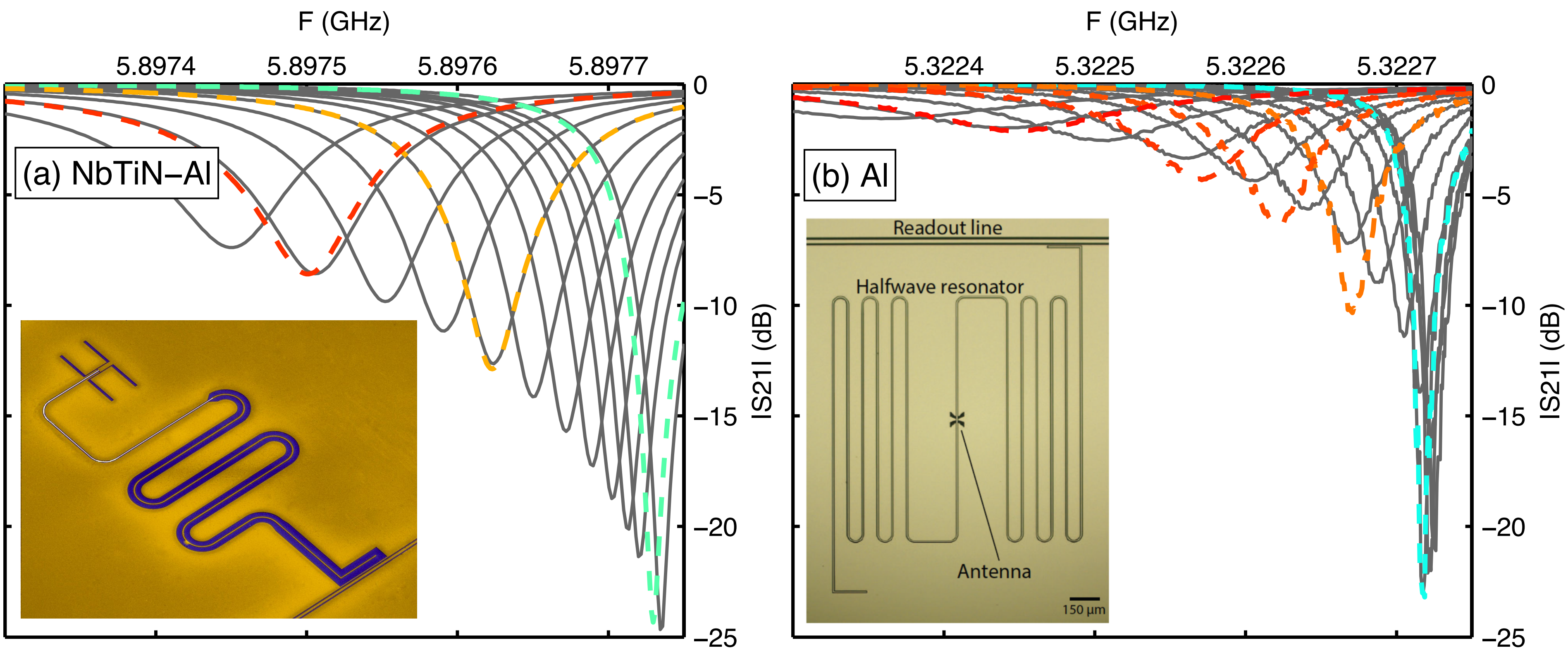
Recent performance improvement





Thermal vs optical response

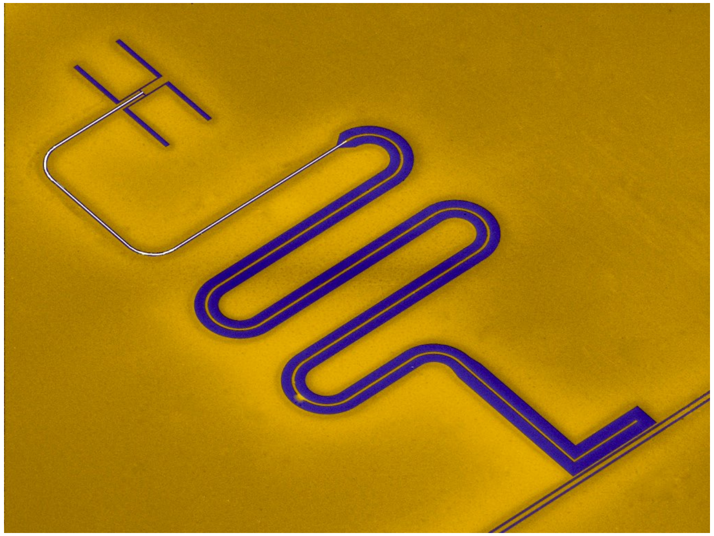
Cooper pairs broken by photon (light) and phonons (temperature)



Hybrid NbTiN-Al KIDs

Performance summary

- Photon-noise-limited operation
  NEP ~ 10^{-17} W/H$^{0.5}$
- MUX factor of ~2000
- Operational range 100 – 1100 GHz
- Optical efficiency determined by antenna
- Thermal and optical response equivalent



MKID based instrumentation

2003 – Day et al., Nature
publication of MKIDs

Sub-mm/mm imagine cameras

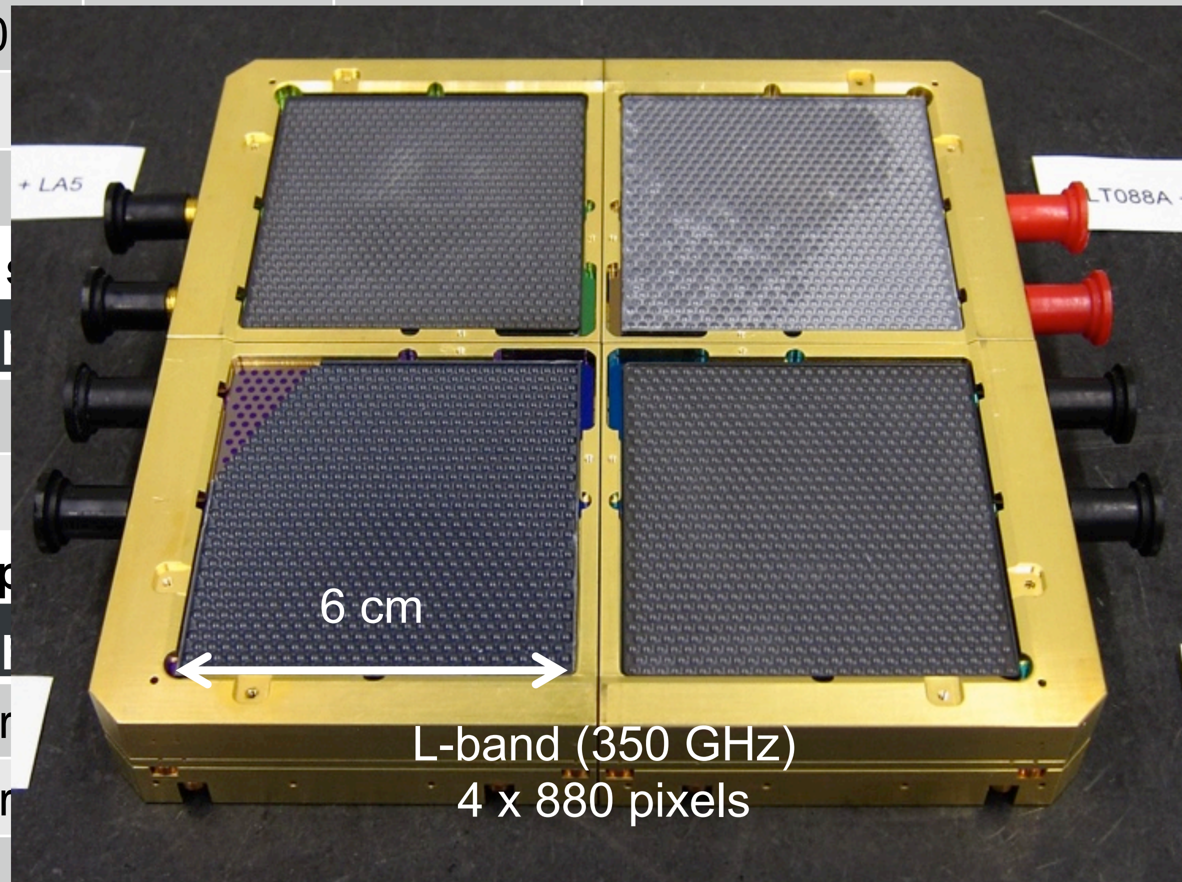
Instrument	telescope	first light	~# pixels	
NIKA (2)	IRAM30			
MAKO	CSO			
A-MKID	APEX			

Sub-mm/mm on-chip s

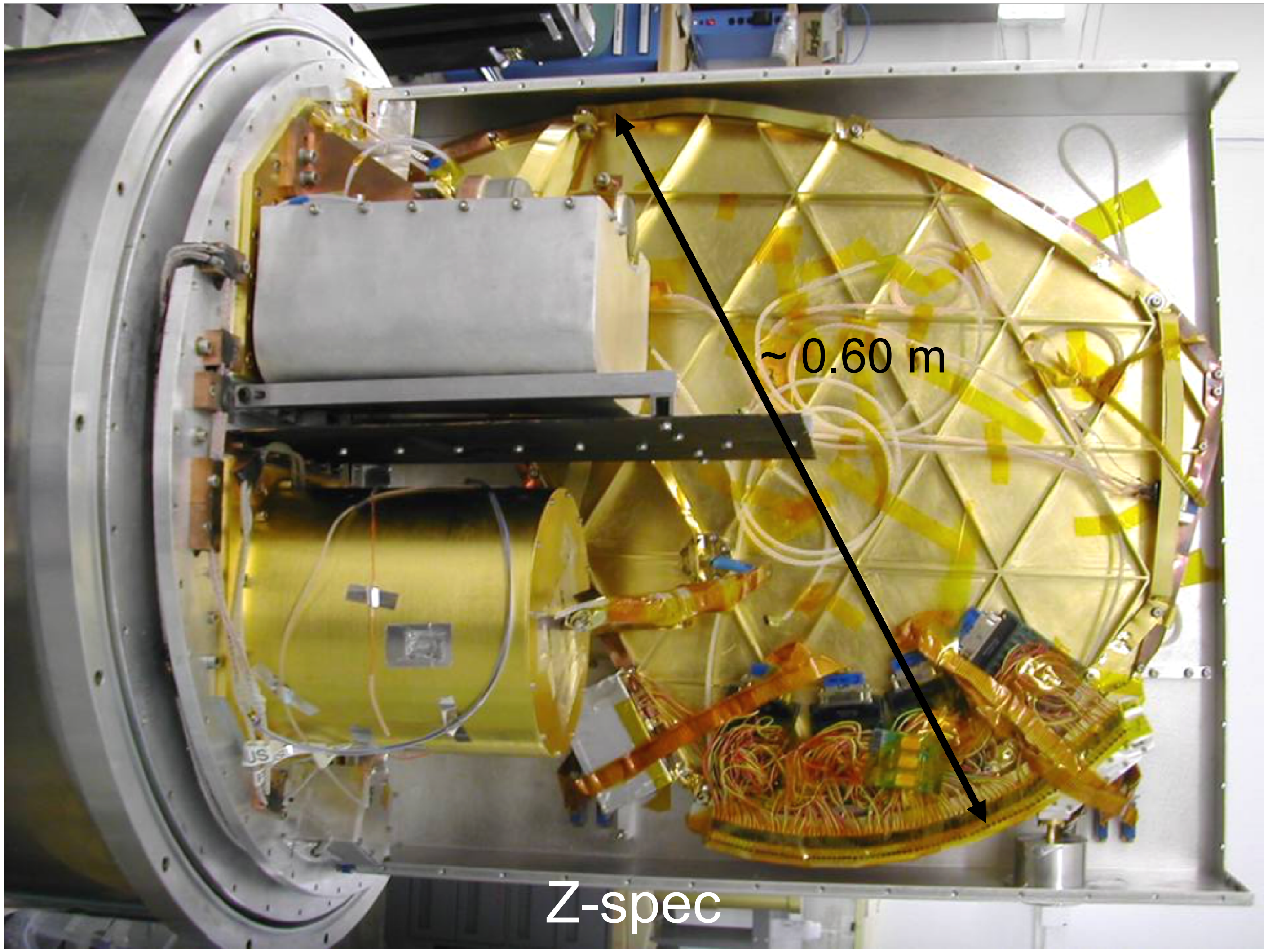
Instrument	telescop
DESHIMA	ASTE
SuperSpec	LMT

VIS-IR integral field sp

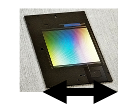
Instrument	telescop
ARCONS	Palomar
DARKNESS	Palomar
MEC	Subaru



Advantage of on-chip spectrometry

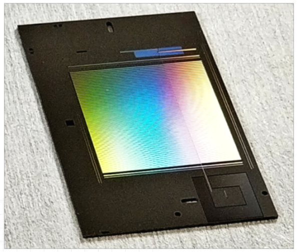


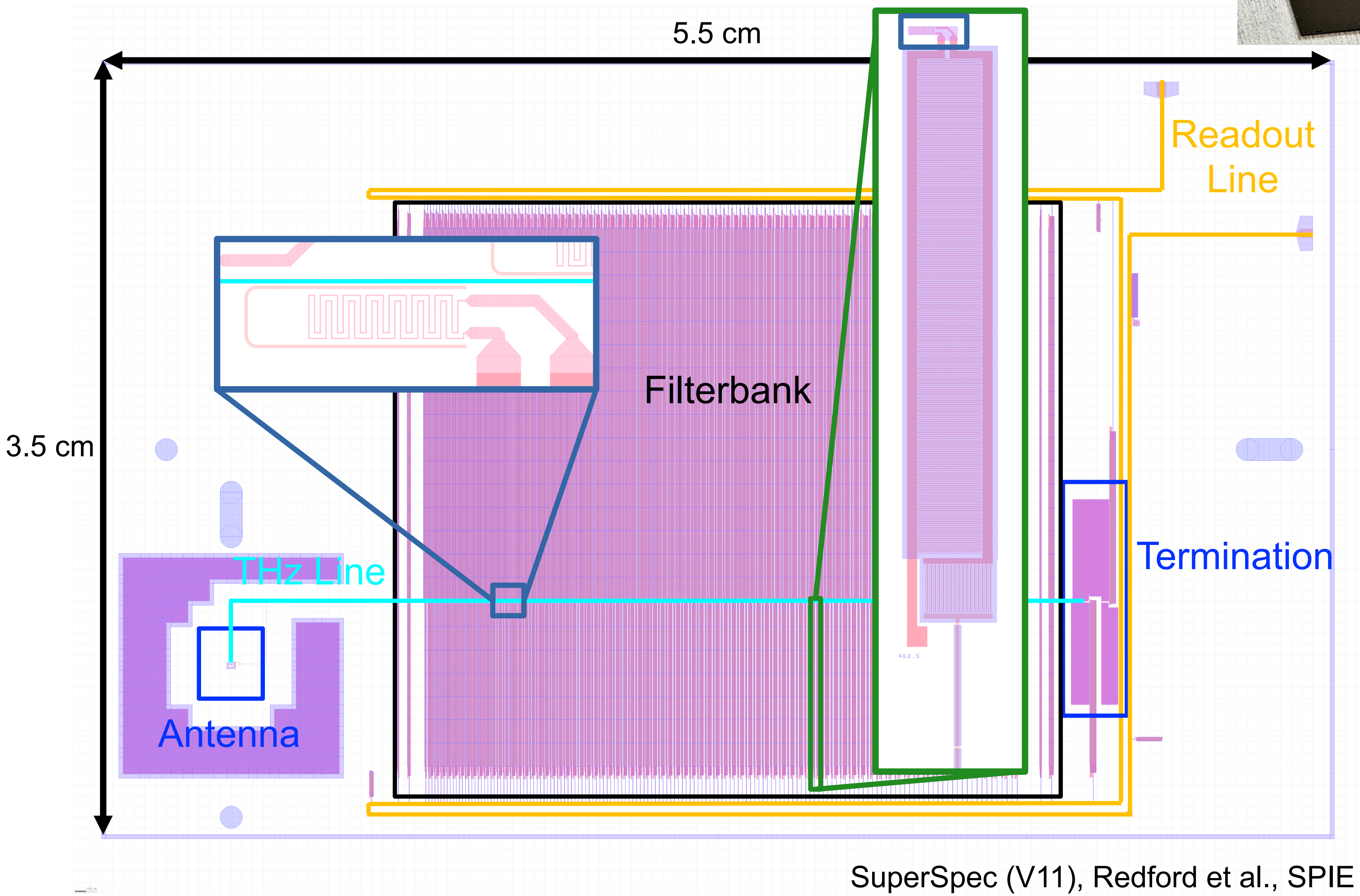
SuperSpec



~ 5 cm

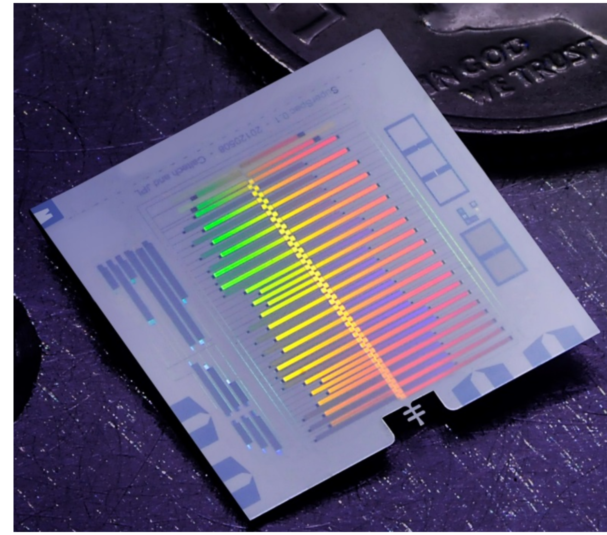
Sub-mm/mm on-chip spectrometry

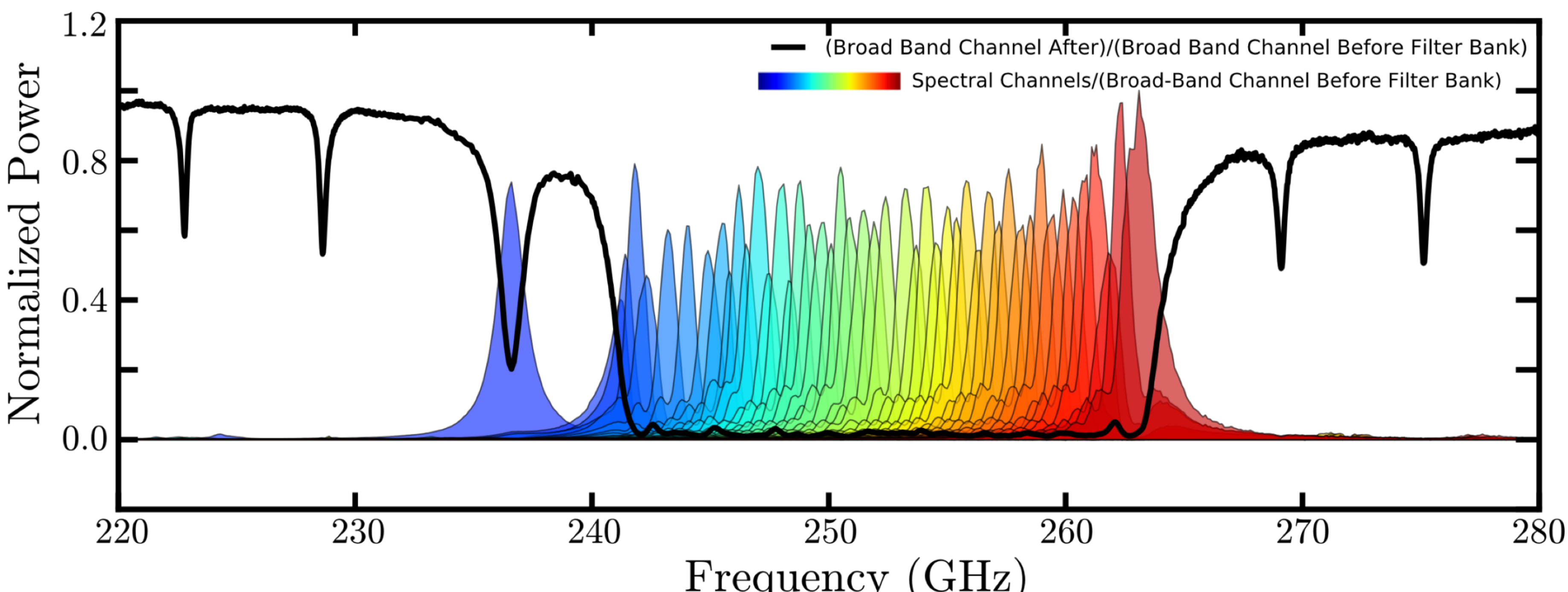




SuperSpec (V11), Redford et al., SPIE (2018)

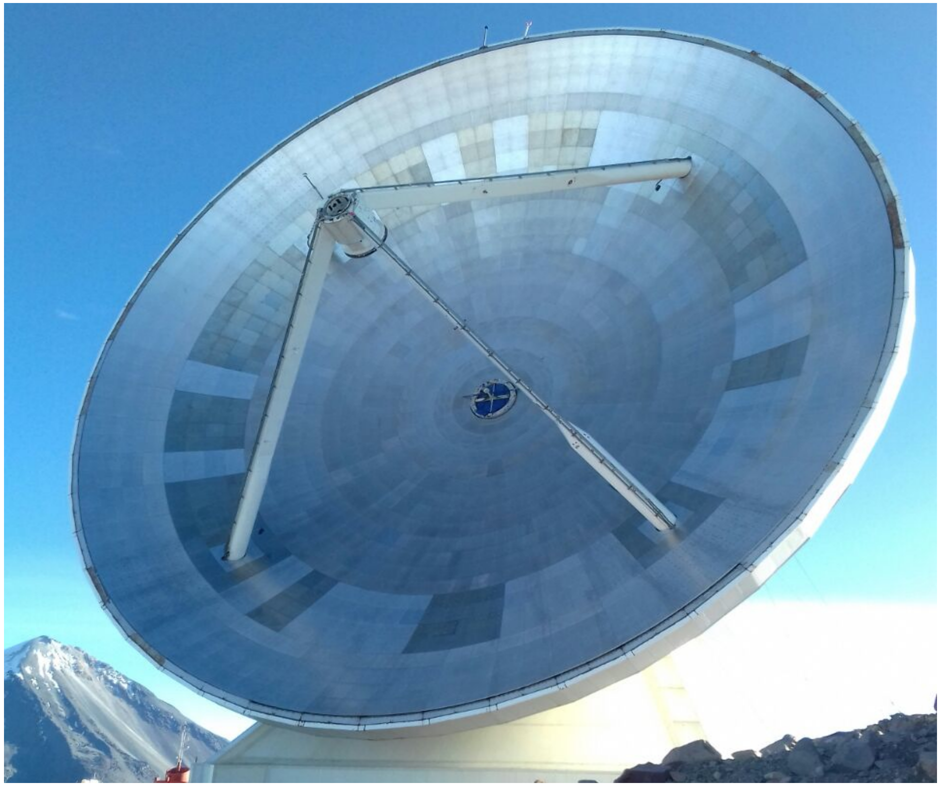
SuperSpec 50-channel



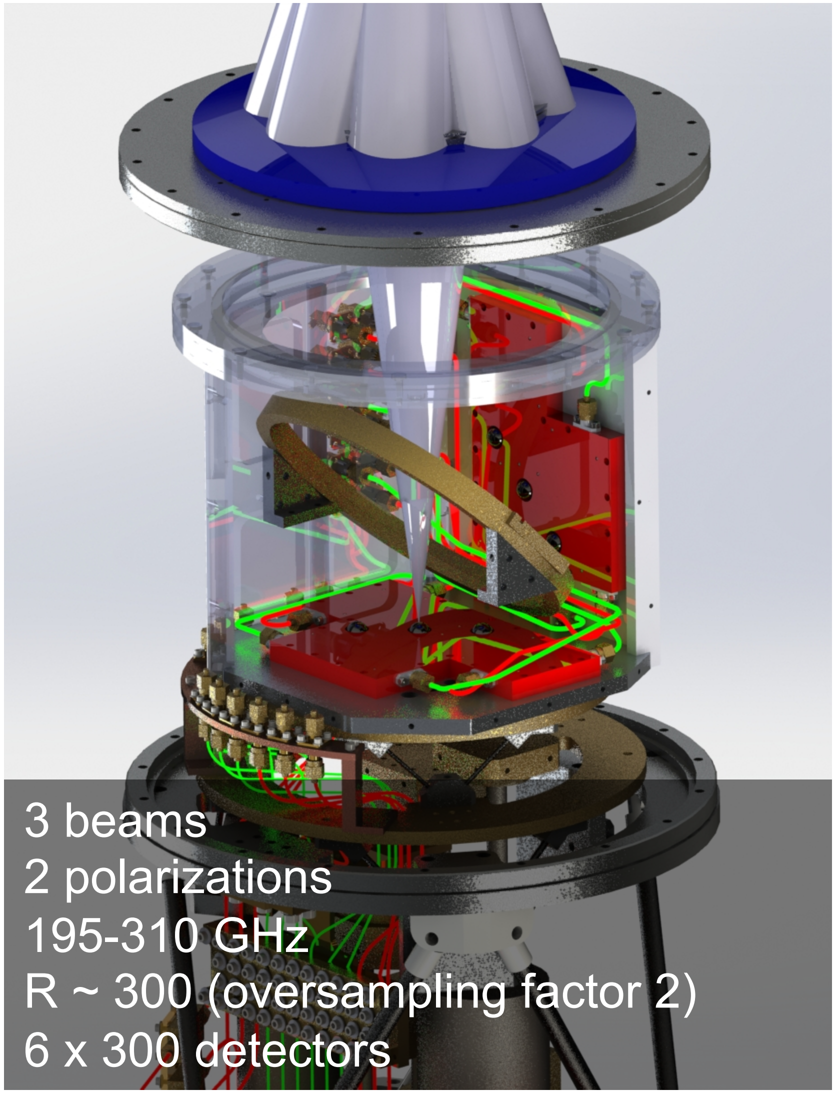


Hailey-Dunsheath et al., JLTP (2018)

SuperSpec @ LMT



Large Millimeter Telescope
Cerro La Negra, Mexico
50 m



3 beams
2 polarizations
195-310 GHz
R ~ 300 (oversampling factor 2)
6 x 300 detectors

Conclusion

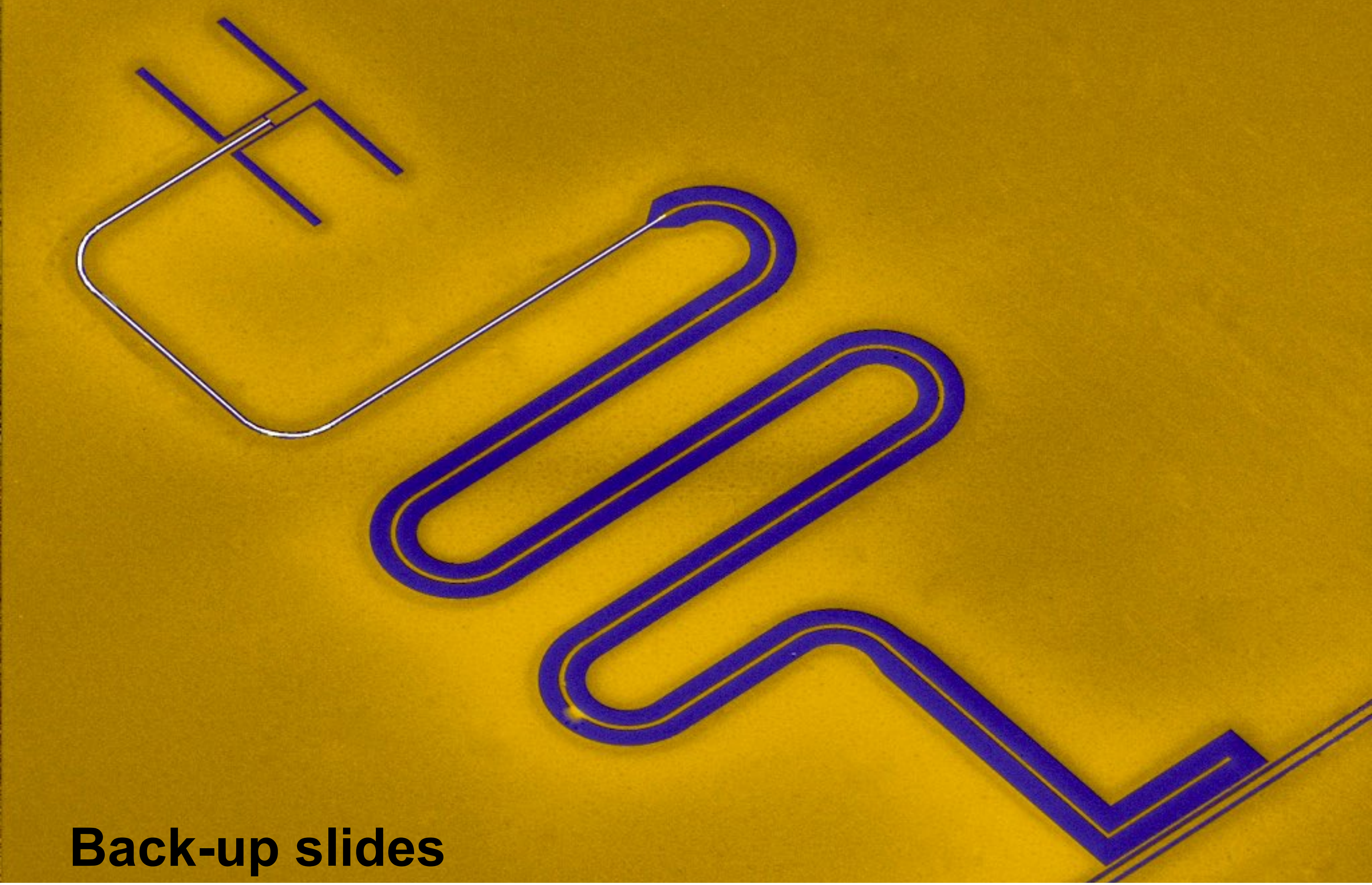
Antenna-coupled hybrid NbTiN-Al KIDs have shown:

- Photon noise limited NEP down to 4×10^{-19} W/Hz$^{0.5}$
- MUX factors of 1000
- Flexibility to operate between 100 – 1000 GHz
- Antenna allows maximum coupling to telescope
- Equivalence between dark and optical response
- Now employed by A-MKID (APEX) and DESHIMA (ASTE)

MKID based instruments are rapidly being deployed on ground-based observatories for both imaging and spectroscopic applications

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov



Back-up slides

Reinier Janssen
March 28, 2019

Jet Propulsion Laboratory
California Institute of Technology

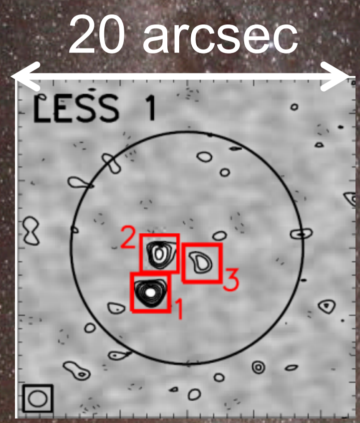
ALMA vs APEX

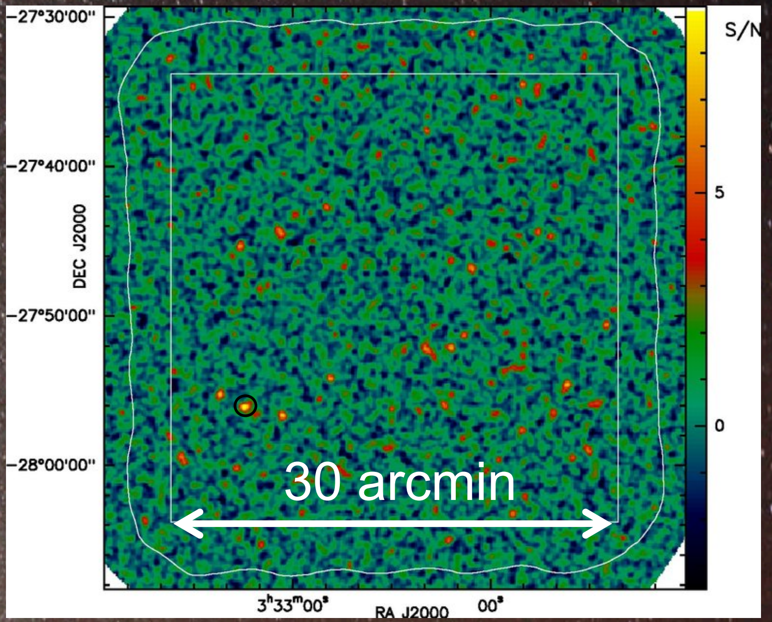
State of the Art in Sub-mm Astronomy

LESS
ECDFS: 0.5x0.5 deg^2
LABOCA (350 GHz)
900 arcmin^2 in 310 hours

ALESS
126 sources inside ECDFS
ALMA Band 7 (355 GHz)
0.065 arcmin^2 in 4.5 hours

Total sky
1.5×10^8 arcmin^2





Future instrumentation for FIR astronomy

Hybrid NbTiN-Al MKIDs enable kilopixel ground-based instruments

Type	F/ΔF	F range	Power per pixel	NEPph ($W/Hz^{-0.5}$)	# pixels
AMKID	3	50 – 950 GHz	10-50 pW	$>3x10^{-16}$	10^5
DESHIMA	1000	100 – 950 GHz	10-100 fW	$>1x10^{-17}$	$>10^5$
CMB observatory, **space**	3	50 – 500 GHz	~100 fW	$4x10^{-18}$	10^3
SpaceKIDs	3	1-10 THz	30 – 300 aW	$>2x10^{-19}$	10^4
Single dish spectrometer, **space**	1000	0.8-10 THz	0.05 – 0.5 aW	$>0.5x10^{-20}$	10^4

AMKID

World’s largest sub-mm camera
with ultimate ground-based sensitivity
for APEX telescope

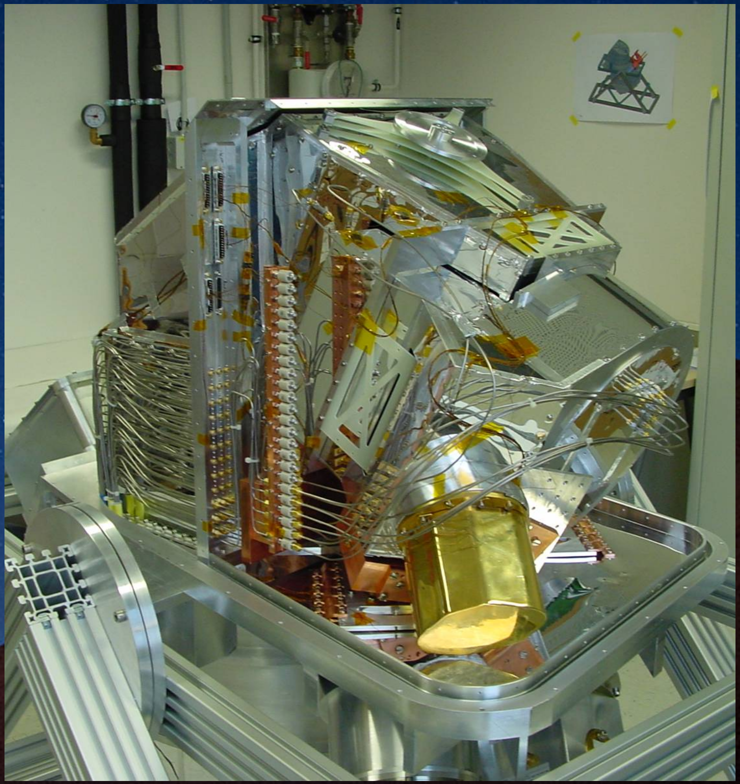
350 GHz	850 GHz
4 x 880 pixels	4 x 5 x 1080 pixels
3520 pixels	21600 pixels

Covering full 15x15 APEX FoV

Max-Planck-Institut für Radioastronomie

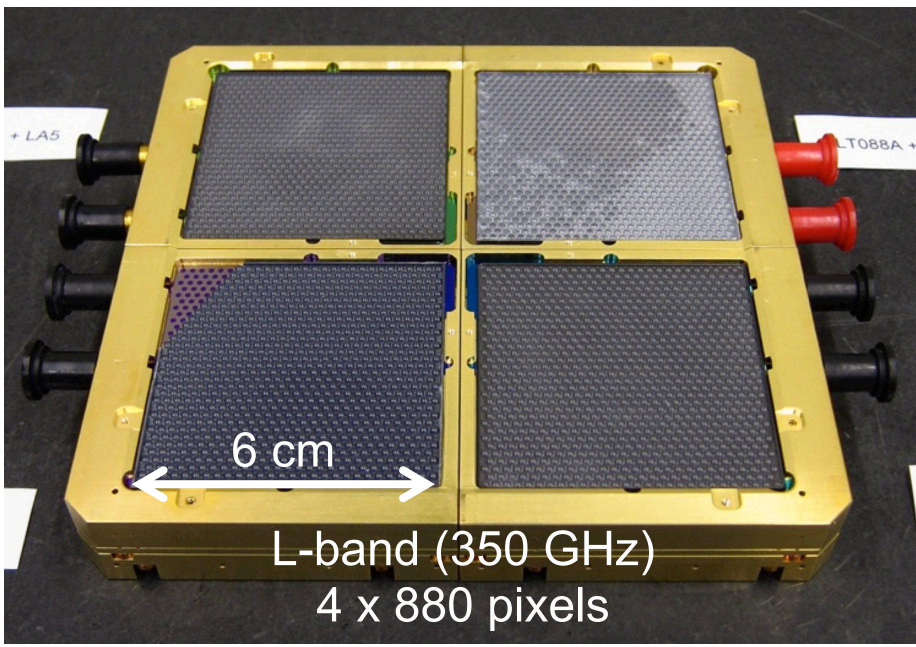
TU Delft Delft University of Technology

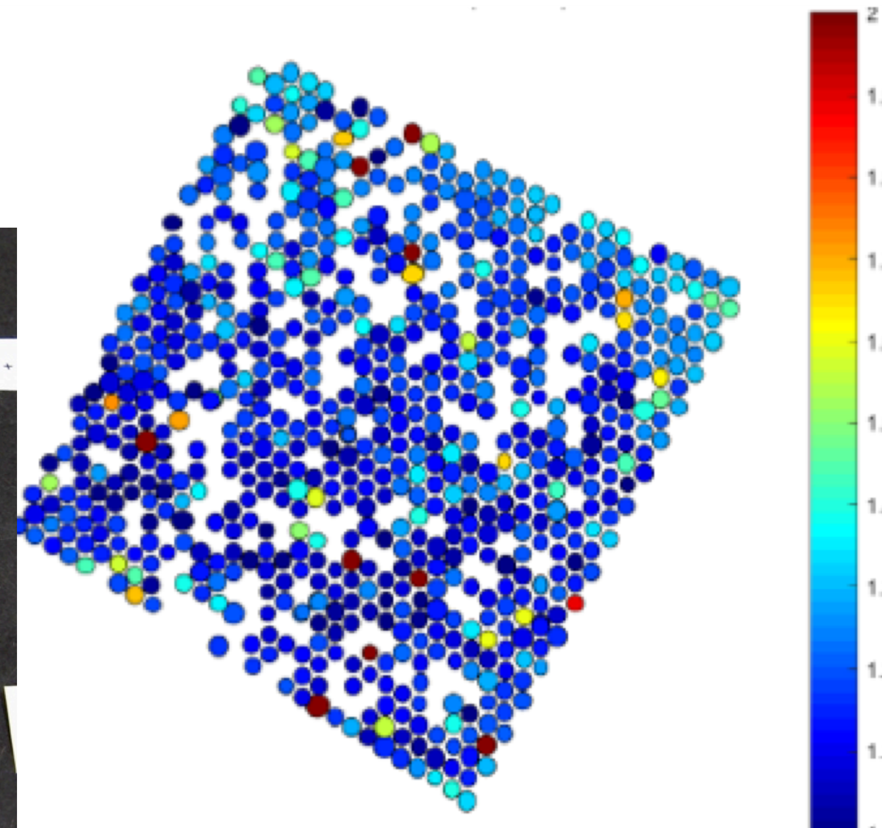
SRON Netherlands Institute for Space Research



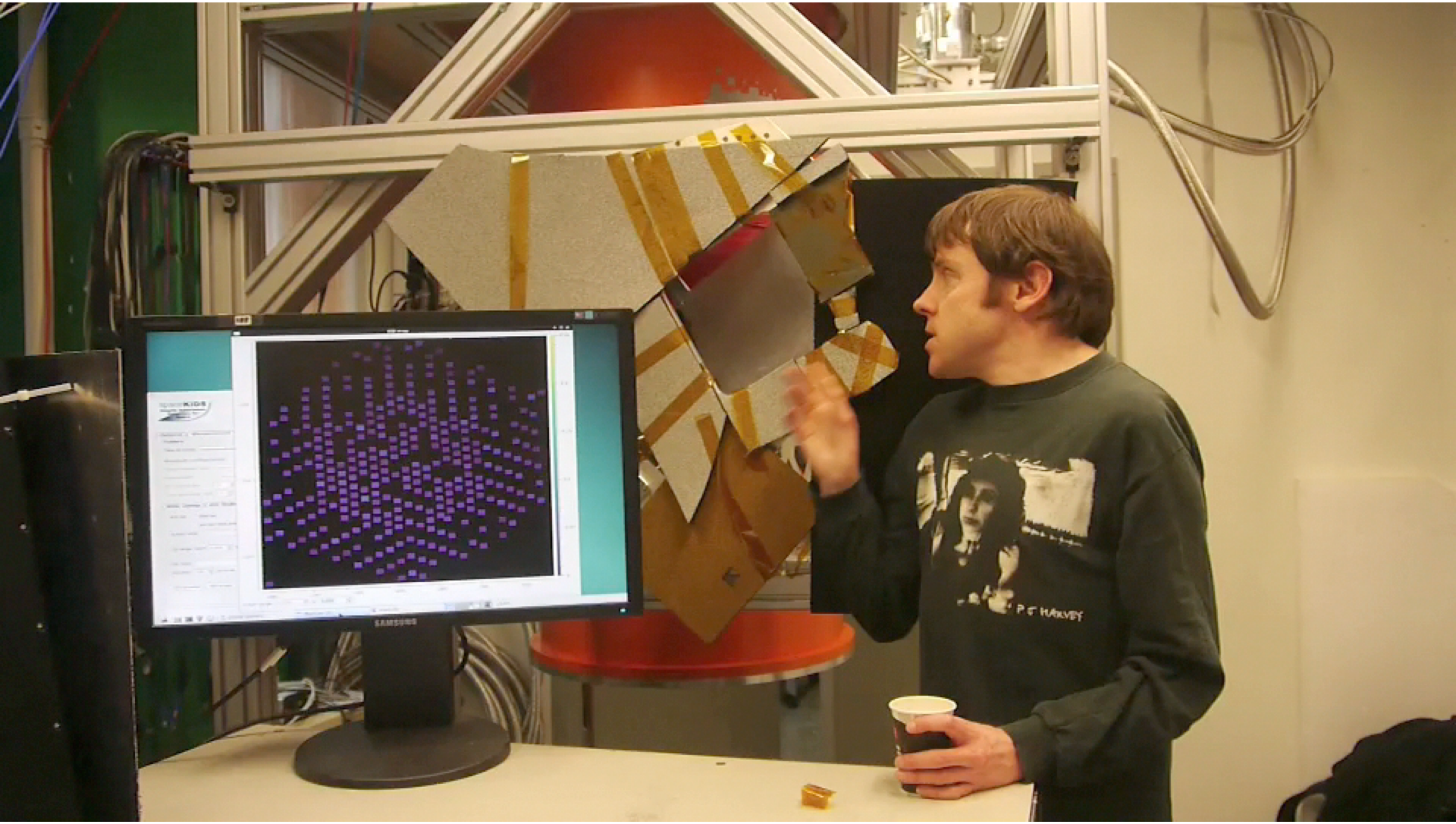
AMKID detector performance

- Background limited sensitivity
- 95% of theoretical efficiency
- 85% pixel yield
- Very uniform sensitivity



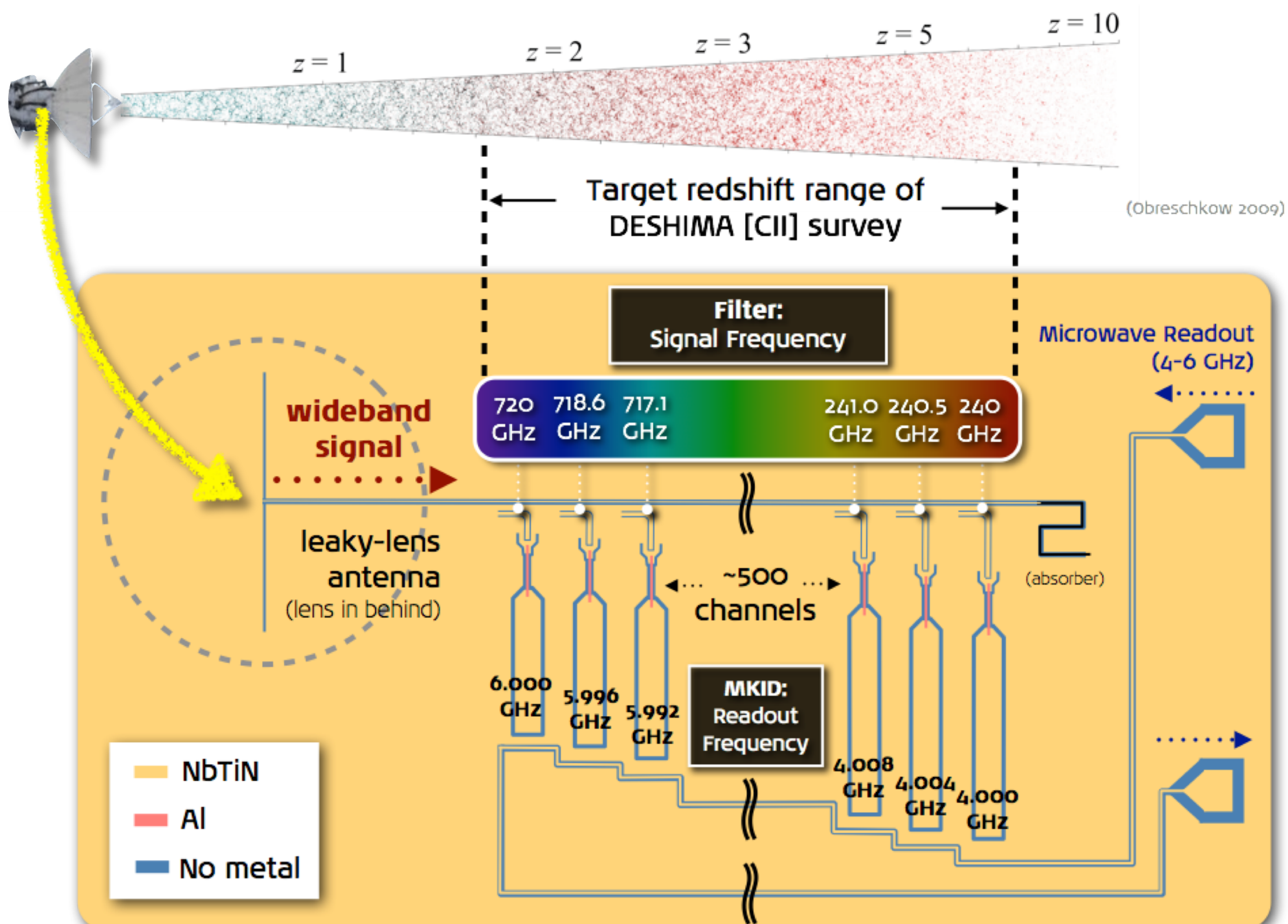


AMKID detector performance



DESHIMA

Superconducting on-chip spectrometer



Final system

1 spatial pixel

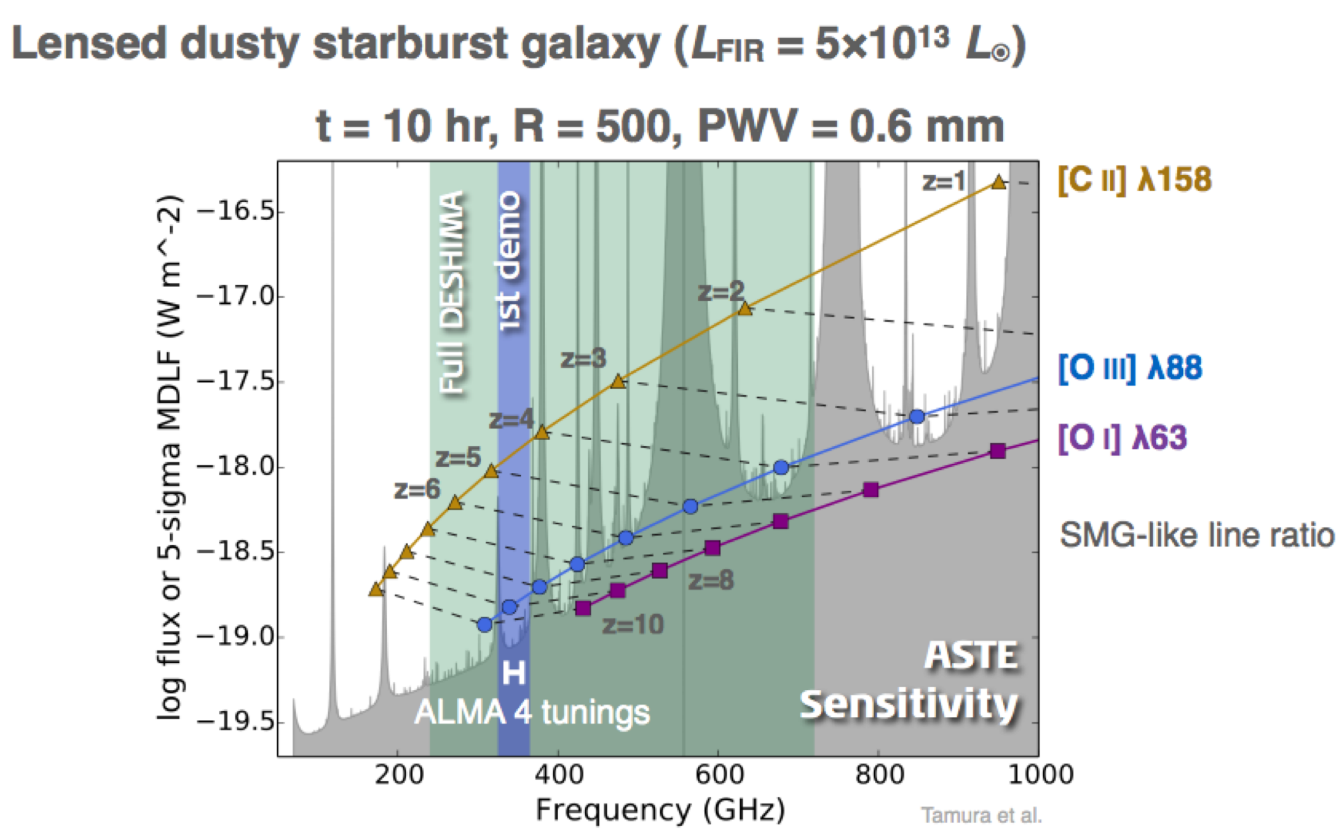
240 – 790 GHz

F/dF = 500

η_{system} ~ 10%

DESHIMA

Superconducting on-chip spectrometer



Final system

1 spatial pixel

240 – 790 GHz

F/dF = 500

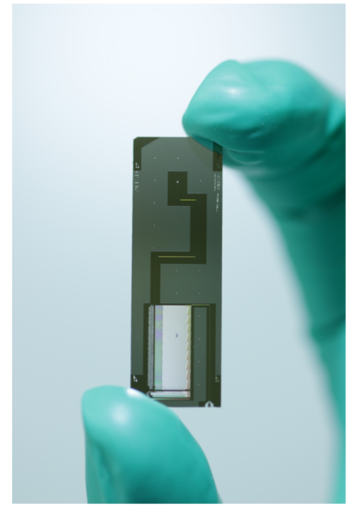
η_{system} ~ 10%

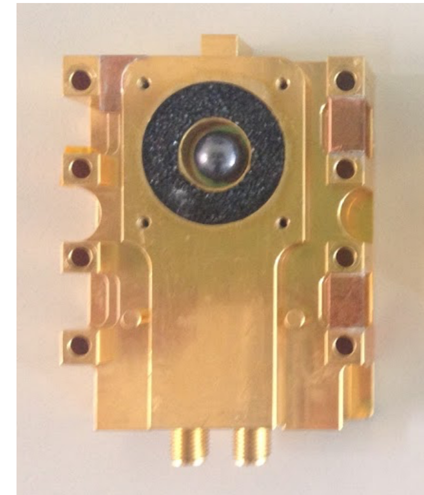
DESHIMA

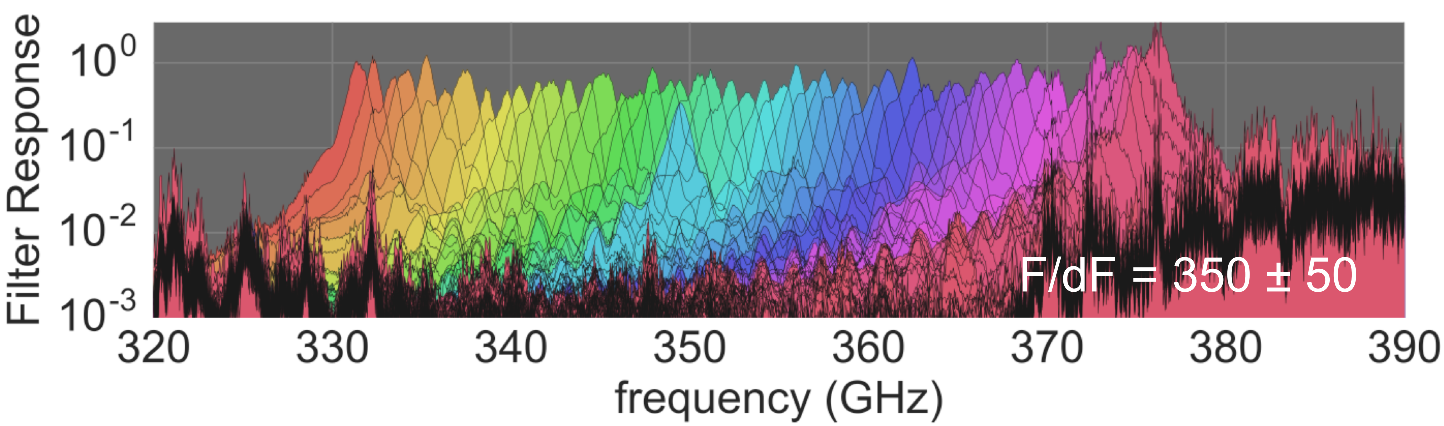
First light on ASTE in fall 2017:

- 1 spatial pixel
- 49 spectral channels
- F/dF = 350
- F_{range} = 326-368 GHz
- Optical system efficiency ~2%
- Yield = 100%

Endo et al., arXiv 1901.06934v1



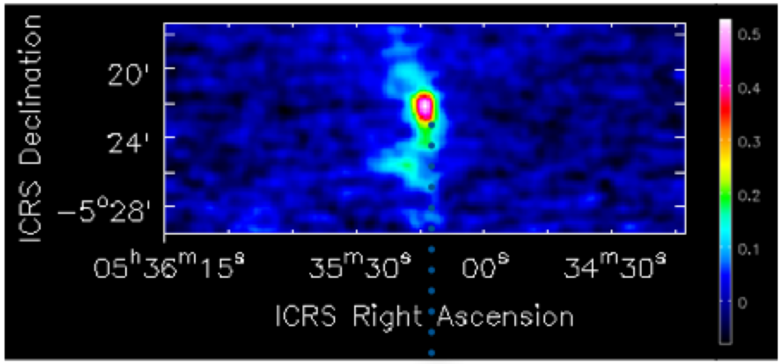


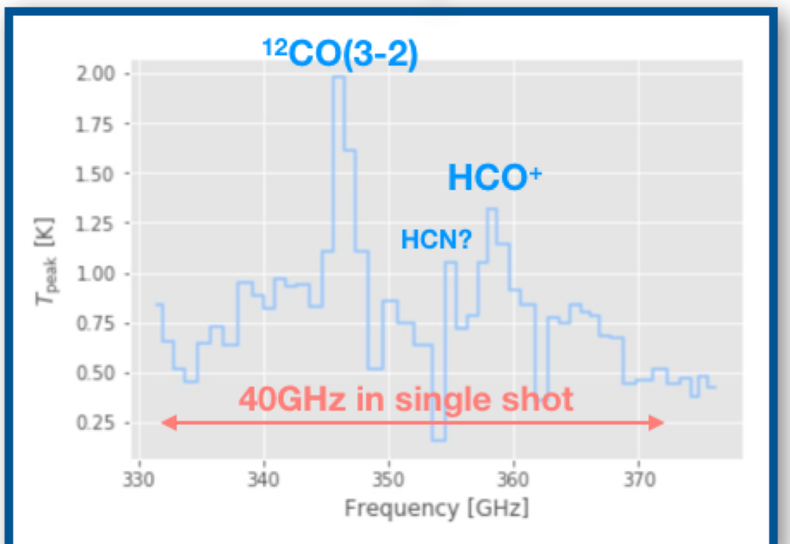


First-light showcase

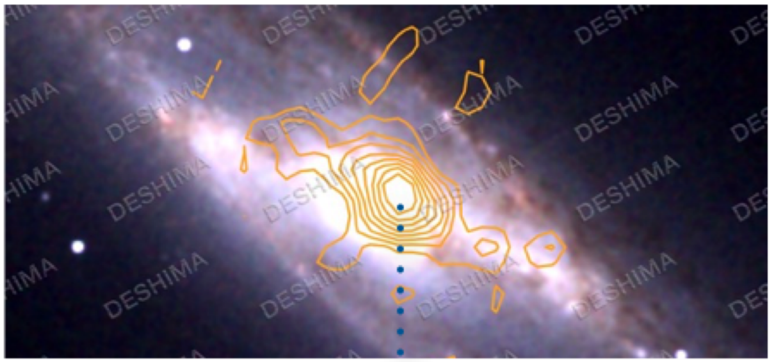
Preliminary results! – Many thanks to A. Endo (PI DESHIMA)

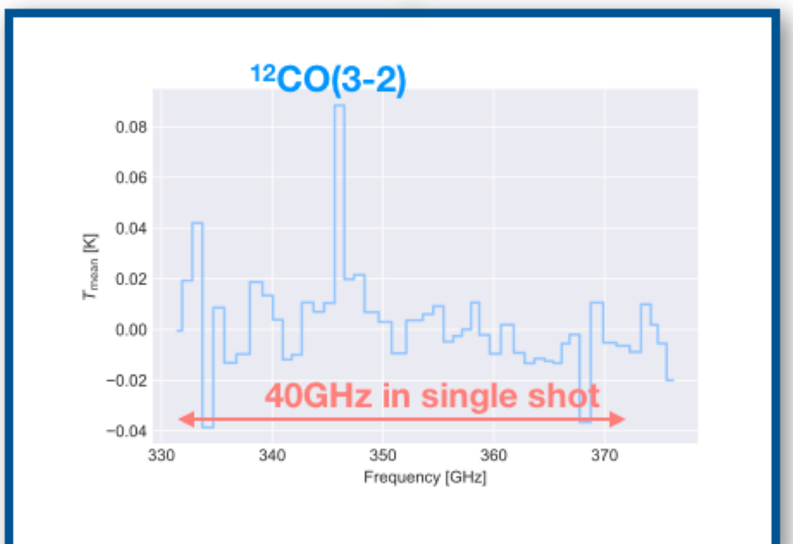
Orion Nebula (continuum map)





NGC253 (CO(3-2) map)

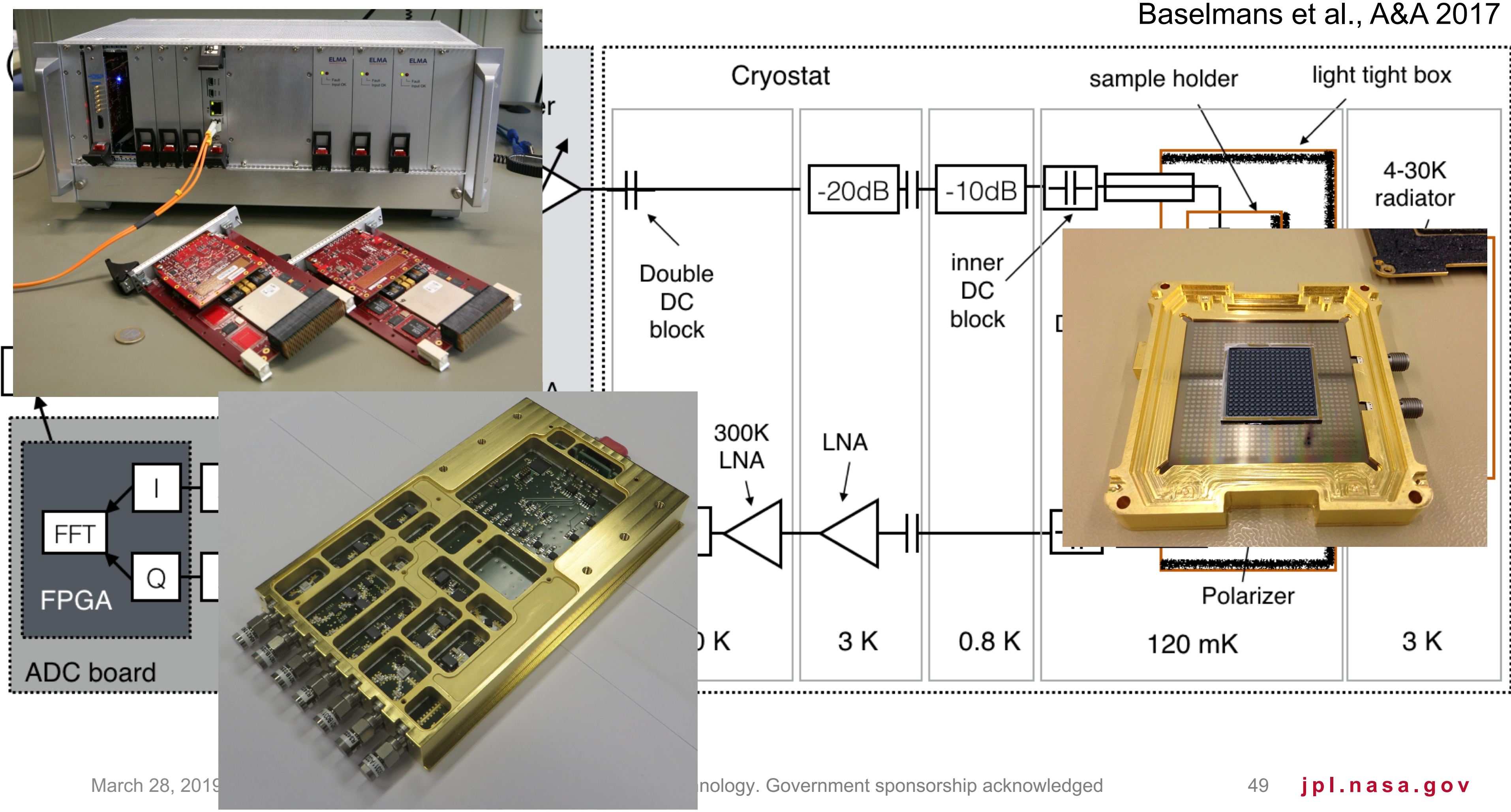




SpaceKIDs

Kilopixel KID-based demonstrator system for low background space-based applications

Baselmans et al., A&A 2017

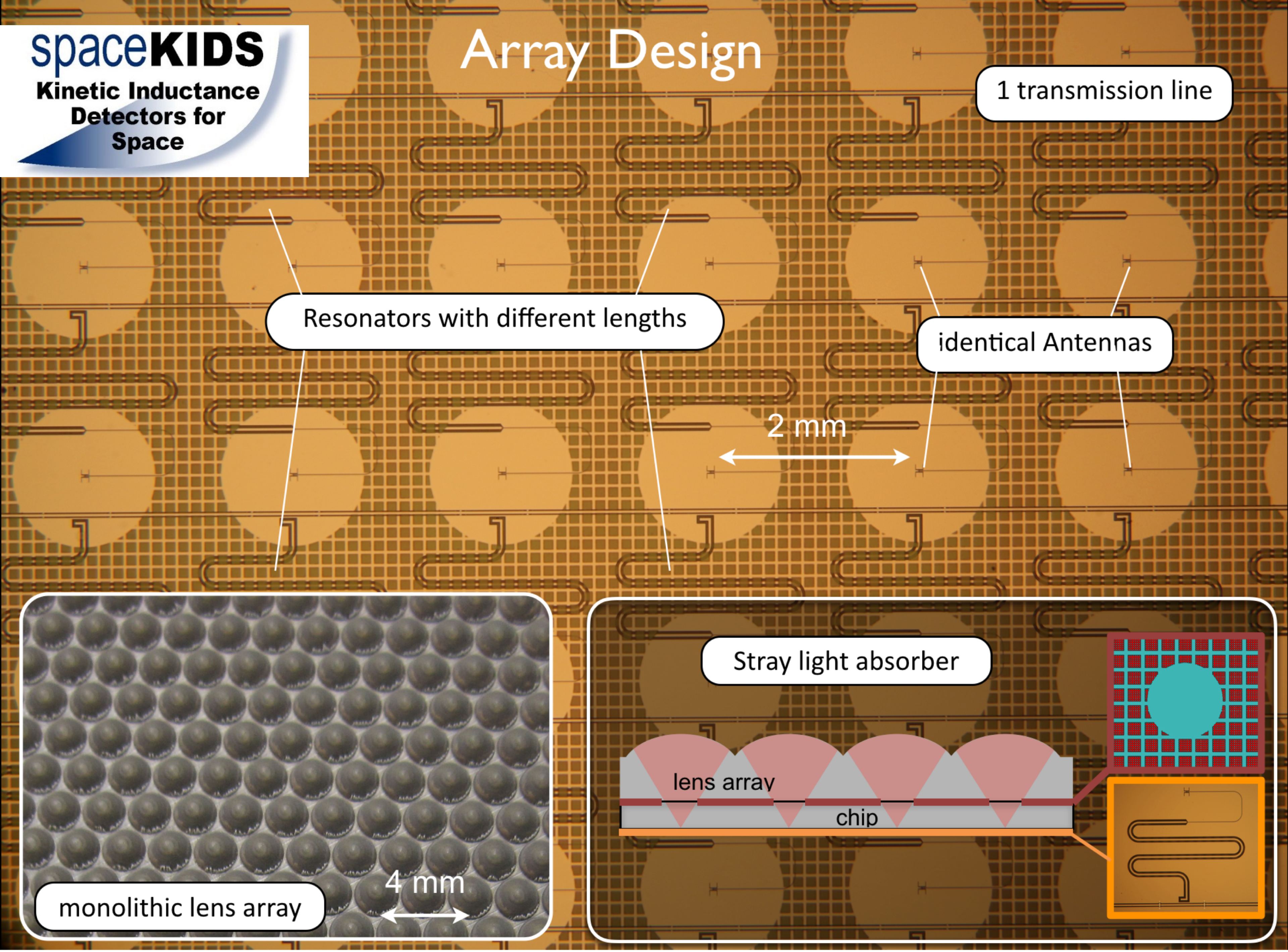


SpaceKIDs

Kilopixel KID-based demonstrator system for low background space-based applications

spaceKIDS Kinetic Inductance Detectors for Space

	MUX (factor)	λ (μm)	λ/Δλ	NEP_{det} ($W/Hz^{-0.5}$)	Absoption Efficiency	Dynamic Range	Cosmic Ray dead time	Cross talk	1/f knee	Yield
Baseline	500	350	5	5×10^{-19}	>0.5	>1000	<30%	<-20 dB	<0.5 Hz	>60%
Goal	1000	200	1.5	1×10^{-19}	>0.7	$>10^{4}$	<10%	<-30 dB	<0.1 Hz	>70%
Achieved	961	350	1.35	3.3×10^{-19}	0.68	10^{5}	4%	-34 dB	0.5 - 1 Hz	83%

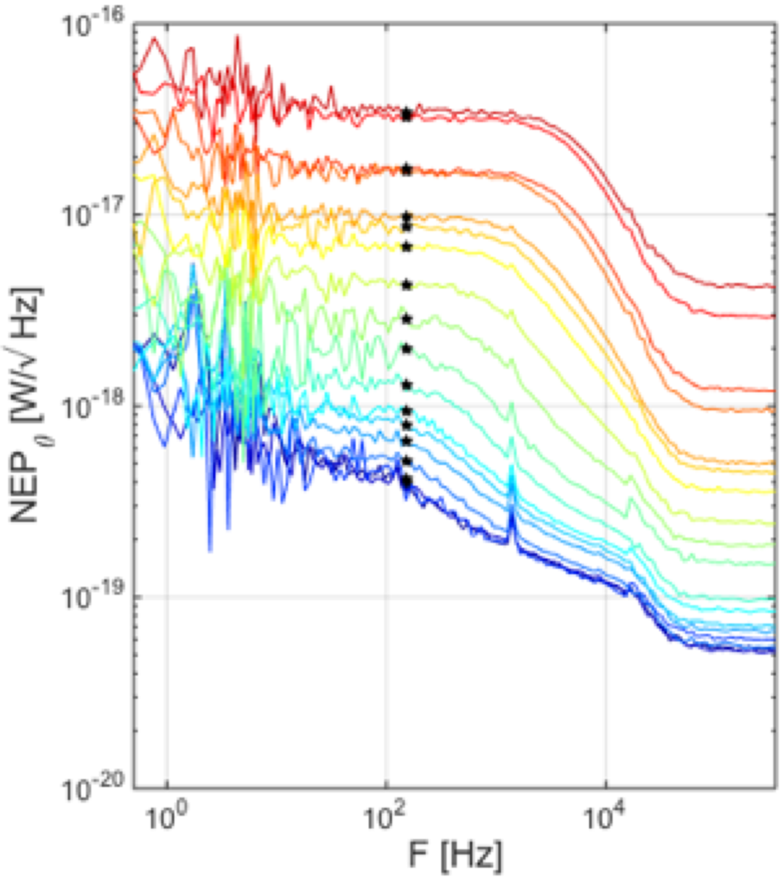


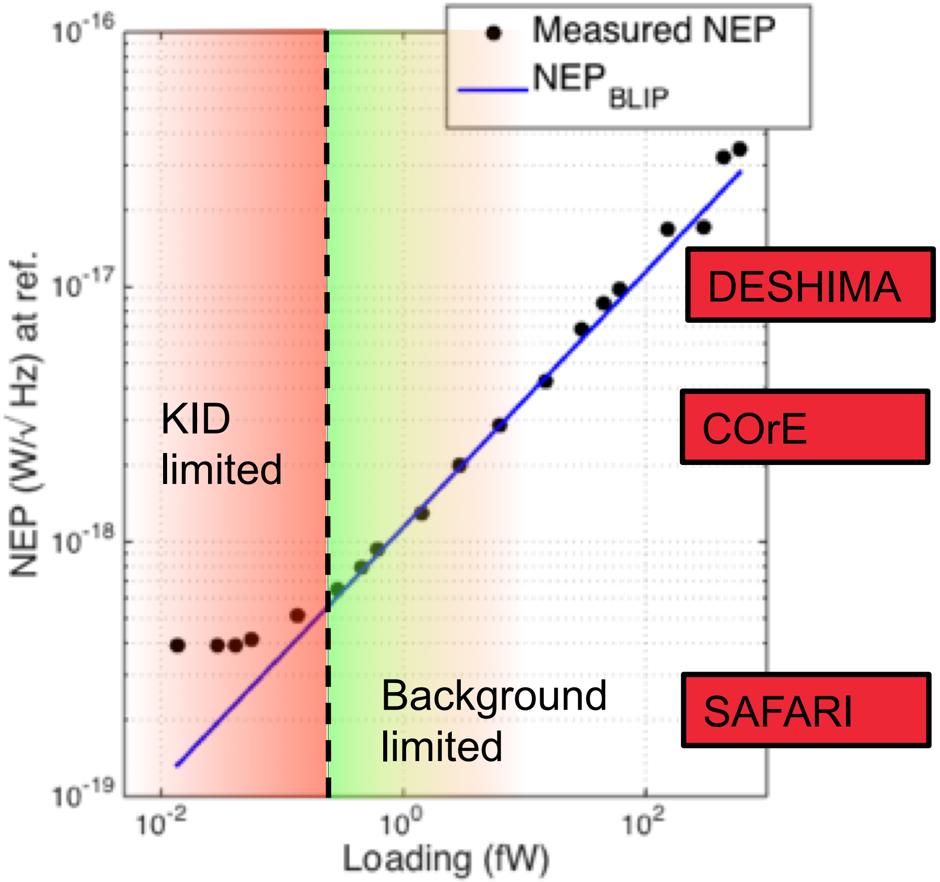
spaceKIDS
Kinetic Inductance Detectors for Space
Array Design
1 transmission line
Resonators with different lengths
identical Antennas
2 mm
Stray light absorber
lens array
chip
monolithic lens array
4 mm

SpaceKIDs

Sensitivity

spaceKIDS
Kinetic Inductance Detectors for Space



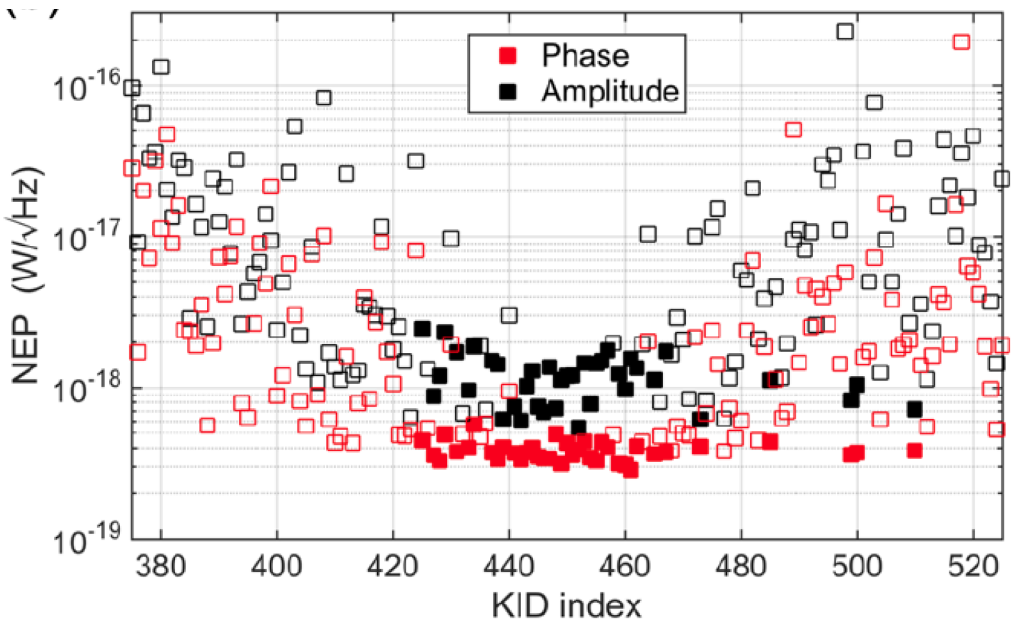


SpaceKIDs

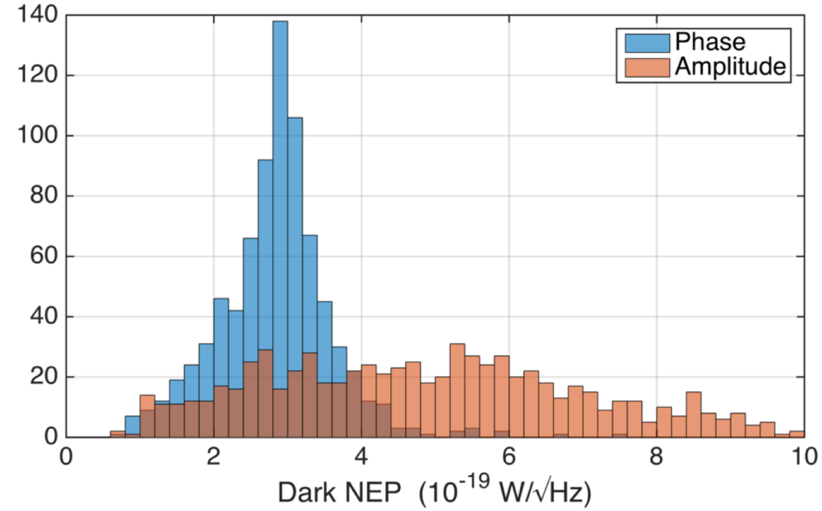
Sensitivity

spaceKIDS Kinetic Inductance Detectors for Space

Optical NEP



Dark NEP

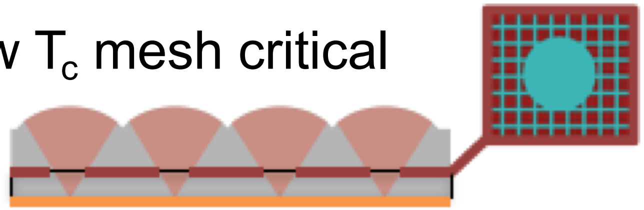


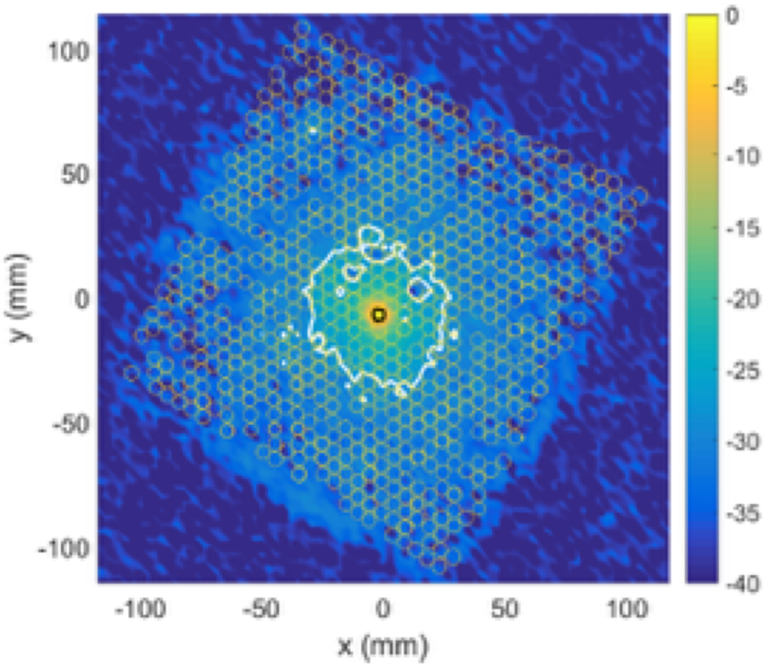
SpaceKIDs

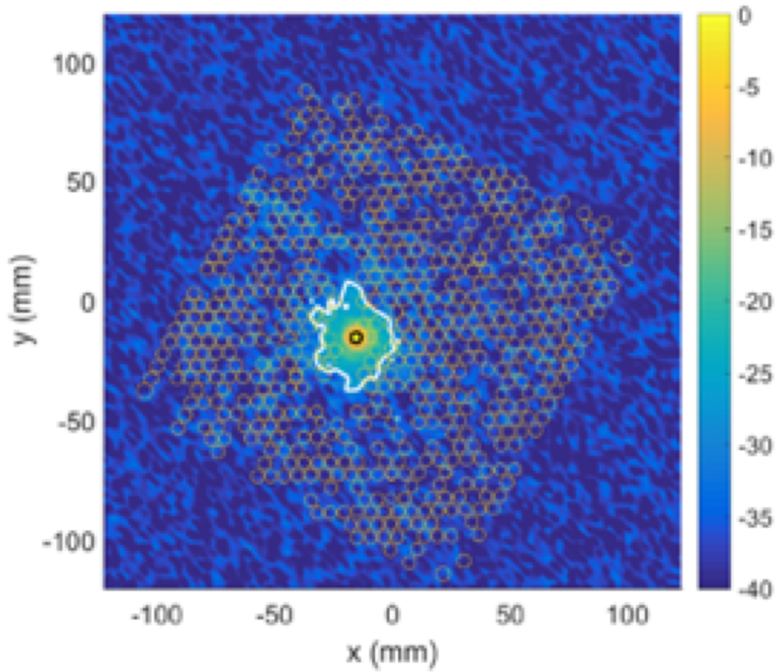
High fidelity imaging

spaceKIDS
Kinetic Inductance Detectors for Space

Low T_c mesh critical







SpaceKIDs

Cosmic Rays

Single glitches with τ ~ 1 ms

Fraction dead time

- Earth: $3.2\text{x}10^{-4}$
- L2 estimate: ~4%
- L2 without mesh: 16-20%